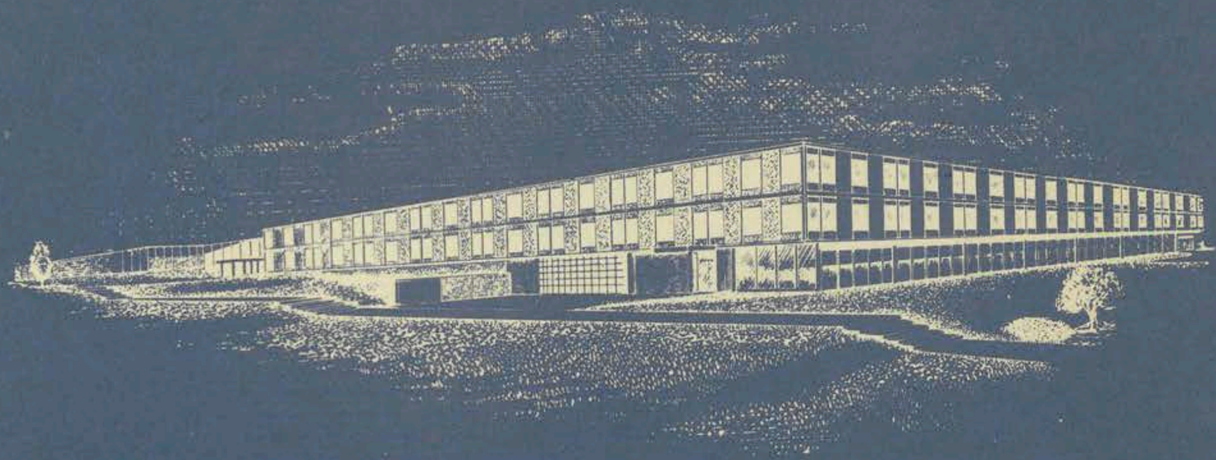
11-1967

Report on Research, School of Engineering, Air Force Institute of Technology, 1962-1966

Air Force Institute of Technology



REPORT ON RESEARCH

SCHOOL OF ENGINEERING
AIR FORCE INSTITUTE OF TECHNOLOGY
AIR UNIVERSITY

1962 - 1966

Archives
Series X
1962-66
c3
(circ)

REPORT ON RESEARCH

SCHOOL
OF
ENGINEERING

AIR
FORCE
INSTITUTE
OF
TECHNOLOGY

AIR
UNIVERSITY

WRIGHT-
PATTERSON
AIR
FORCE
BASE
OHIO

Nothing is more important to the security of the free world than United States technological leadership in the space age. The Institute has made many outstanding contributions to the building of the greatest military power in history; a power dedicated to the preservation of peace and freedom throughout the world.

FOREWORD

The United States Air Force, in an effort to sustain its technological superiority, makes heavy demands on the nation's scientific, engineering, and managerial resources and talents. To assist in this effort, the Air Force Institute of Technology (AFIT) is providing highly specialized graduate programs specifically tailored to Air Force needs—programs that are constantly re-evaluated, modified, and updated so as to keep pace with the latest technological and scientific developments of the space age.

Since the AFIT School of Engineering offers predominantly graduate programs, strong emphasis is placed on research by both faculty and students. Much of this research is sponsored and supported by Air Force laboratories. Consequently, AFIT's endeavors in this area serve a dual purpose—they fulfill an academic requirement and, at the same time, make a direct contribution to the research and development programs of the Air Force. Over the years the School of Engineering has significantly enhanced the scientific and technological competence of the Air Force. This has been accomplished, in part, through research projects, some of which have been conducted jointly with Air Force laboratories, and through consulting assistance made available to other Air Force organizations. The School has, however, made its greatest contribution to this effort by providing a source of officers possessing highly specialized knowledge to match the exacting requirements for the numerous technical and scientific assignments within the Air Force.

This report is published for those civilian and military educational and research organizations that may be interested in information on the research activities of the AFIT School of Engineering.

Ernest A. Pinson

ERNEST A. PINSON, Major General, USAF
Commandant

Wright-Patterson Air Force Base, Ohio
November 1967

CONTENTS

air force institute of technology	1
school of engineering	5
faculty	11
aeronautical engineering	19
electrical engineering	29
humanities	49
mathematics	55
mechanical engineering	61
mechanics	73
physics	91
systems management	103
nuclear engineering test facility	107
publications	111
technical reports	121

AIR FORCE INSTITUTE OF TECHNOLOGY

The history of the Air Force Institute of Technology (commonly known as AFIT) can be traced as far back as 1919 when the Air School of Application was established at McCook Field, Dayton, Ohio, as an aeronautical school within the Army. In 1920 the School was redesignated the Air Service Engineering School; in 1927 it became the Air Corps Engineering School at the new installation named Wright Field in honor of Dayton's celebrated aviators, Orville and Wilbur Wright. The School was renamed the Air Force Institute of Technology in 1947 and is now operated as a component of Air University which has its headquarters at Maxwell Air Force Base, Alabama. Today, the Institute is located at Wright-Patterson Air Force Base near Dayton, Ohio, and its proximity to the largest laboratory complex of the Air Force provides an excellent environment for faculty and student research in support of the Air Force mission.

The Air Force Institute of Technology is organized into four schools and centers:

- School of Engineering
- School of Systems and Logistics
- Civil Engineering Center
- Defense Weapon Systems Management Center

The School of Engineering offers undergraduate and graduate programs leading to B.S., M.S., and D.Eng.Sc. degrees in engineering. A brief description of these programs is given in a separate section.

The School of Systems and Logistics offers two main programs: a Graduate Logistics Program leading to an M.S. degree in logistics management, and a Continuing Education Program consisting of thirty-five short courses designed to provide further education for professional logisticians holding managerial positions in maintenance, supply, transportation, and procurement.

The Civil Engineering Center offers short courses for civil engineers to prepare them for specific assignments in the Air Force. Currently, the following courses are offered: Base Civil Engineer, Executive Engineering, Pavements Engineering, Control Center Management, Network Planning, Applied Engineering, and Cold Regions Engineering.

The Defense Weapon Systems Management Center offers several courses for senior military and civilian managers of major weapon systems, and conducts research and development of management concepts, doctrines, and techniques.

In addition to the four schools, AFIT monitors a Civilian Institutions Program. Students in this program, which number about 5,200 and include both officers and airmen, are enrolled in some one hundred civilian institutions throughout the United States and overseas.

COMMANDANT
Maj Gen. Ernest A. Pinson

DEPUTY COMMANDANT
Col. Marshall F. Sanders

ACADEMIC DIRECTOR
Dr Howard W Barlow

DIRECTOR
PLANS AND PROGRAMS
Col. A. E. Haveman

SCHOOL OF ENGINEERING
Dr. R. H. Downing, *Dean*

SCHOOL OF SYSTEMS AND LOGISTICS
Col. R. W. Amick, *Dean*

CIVIL ENGINEERING CENTER
Col. R. H. Armstrong, *Director*

DEFENSE WEAPON SYSTEMS MANAGEMENT CENTER
Col. L. F. Blais, *Commandant*

CIVILIAN INSTITUTIONS DIVISION
Col. M. R. Palmer, *Director*

school of engineering

The Air Force Institute of Technology School of Engineering, one of the largest graduate engineering schools in the United States, ranked tenth among the schools awarding M.S. degrees in engineering in 1965, according to the Interim Report on Engineering Education published in 1967 by the American Society for Engineering Education.

The School of Engineering, under the direction of a Dean, comprises eight academic departments, the Air Force Nuclear Engineering Test Facility, and the Minuteman Education Program (Detachment #5) at Malmstrom Air Force Base, Montana. The research programs at the School are under the general direction of an Assistant Dean for Research.

DEAN
Dr. R. H. Downing

ASSISTANT DEAN FOR RESEARCH
Dr. J. S. Przemieniecki

ASSISTANT DEAN
Lt. Col. J. C. Hill, Jr.

DEPARTMENT OF AERONAUTICAL ENGINEERING
Prof. H. C. Larsen, *Head*

DEPARTMENT OF ELECTRICAL ENGINEERING
Col. R. E. Fontana, *Head*

DEPARTMENT OF HUMANITIES
Dr. H. E. Hand, *Head*

DEPARTMENT OF MATHEMATICS
Dr. A. B. Carson, *Head*

DEPARTMENT OF MECHANICAL ENGINEERING
Dr. A. J. Shine, *Head*

DEPARTMENT OF MECHANICS
Dr. D. W. Breuer, *Head*

DEPARTMENT OF PHYSICS
Dr. L. S. Pedrotti, *Head*

DEPARTMENT OF SYSTEMS MANAGEMENT
Lt. Col. L. L. Dunlap, *Head*

AIR FORCE NUCLEAR ENGINEERING TEST FACILITY
Col. P. S. Gwynn, *Director*

MINUTEMAN EDUCATION PROGRAM
MALMSTROM AIR FORCE BASE, MONTANA
Maj. A. J. Kuprenas, *Commander*

The School is presently conducting the following graduate programs: Aerospace-Mechanical Engineering, Aerospace Weapons, Astronautics, Electronics, Guidance and Control, Nuclear Engineering, Reliability Engineering, Space Facilities, Space Physics, Systems Management, and Aerospace Engineering (Malmstrom AFB, Montana). In addition, two undergraduate programs are offered in aerospace and electrical engineering.

A doctoral program in aerospace engineering was recently added to the curriculum, and the first doctoral students were enrolled in June 1965. Preliminary accreditation of this program was granted by the North Central Association of Colleges and Secondary Schools.

The first phase of the doctoral program, which covers a two-year period, consists of a sequence of courses in advanced mathematics, theoretical and applied mechanics, and advanced physics, followed by a series of specialty courses. The second phase of the program consists of a tour of duty of regular length (generally four years) in one of the Air Force research laboratories where each doctoral student, under the guidance and supervision of AFIT faculty, pursues research for his dissertation on a subject pertinent to the mission of the respective laboratory.

GRADUATE PROGRAMS

(M.S. Degrees)

PROGRAM	1962	1963	1964	1965	1966	TOTAL 1962–66
Aeronautical (18)*	30	34	2	—	2	68
Aerospace-Mechanical (21)	—	—	31	32	48	111
Aerospace Weapons (21)	18	17	13	8	—	56
Astronautics (24)	21	25	25	18	1	90
Electronics (18)	19	29	30	33	2	113
Guidance and Control (21)	23	19	22	23	22	109
Materials Engineering (21)	—	—	10	13	—	23
Nuclear Engineering (21)	16	19	19	19	2	75
Reliability Engineering (18)	—	23	13	14	12	62
Space Facilities (24)	—	—	14	8	—	22
Space Physics (21)	—	—	13	25	21	59
Systems Management (15)	—	—	25	23	19	67
Aerospace Engineering (42) (Malmstrom AFB)	—	—	—	17	57	74
TOTAL	127	166	217	233	186	929

UNDERGRADUATE PROGRAMS

(B.S. Degrees)

PROGRAM	1962	1963	1964	1965	1966	TOTAL 1962–66
Aerospace Engineering (24)*	20	16	26	25	19	106
Electrical Engineering (24)	21	24	33	25	26	129
TOTAL	41	40	59	50	45	235

*Numbers in parentheses refer to the length of programs in months.

Faculty

The members of the academic departments, both military and civilian, hold academic ranks ranging from instructor through professor. Over the past few years the faculty has had approximately 90 full-time members. In addition to the regular faculty, highly qualified adjunct and visiting professors from the various Air Force research laboratories at Wright-Patterson Air Force Base have been used to teach advanced courses and supervise thesis projects. Complete lists of present and former faculty are presented in separate sections of this report.

FULL-TIME FACULTY

(Excluding adjunct and visiting professors)

Highest Academic Degree	1962	1963	1964	1965	1966
Ph.D.	21	34	41	48	44
M.S.	56	56	55	48	40
TOTAL	77	90	96	96	84

Since research is one of the most important functions of any institution of higher learning, the faculty members are expected to participate in research programs in their respective areas of responsibility and interest. To accomplish this they must

- Supervise and direct M.S. and D.Eng.Sc. thesis projects and ensure that they are coordinated with or made a part of Air Force research programs.
- Participate in cooperative student research programs with Air Force laboratories.
- Conduct exploratory research with the objective of supplementing research and development programs of the Air Force.
- Participate in joint research projects with Air Force laboratories.
- Contribute to scientific and technical literature.
- Make presentations at conferences and symposia sponsored by the Air Force or by professional societies.
- Provide expert scientific counsel to other Air Force organizations.

Some idea of the performance of the faculty in fulfilling these requirements can be obtained from the following table which provides statistical information on publications, presentations, and research projects during the period of this report.

PUBLICATIONS PRESENTATIONS, AND RESEARCH PROJECTS 1962–66

	1962	1963	1964	1965	1966
Books	1	1	0	2	3
Papers Published in Technical and Scientific Journals	9	22	21	39	72
Presentations at Technical Meetings, Symposia, etc.	11	10	24	54	43
Technical Reports	5	9	9	20	23
New Research Projects	24	26	39	27	45
Active Research Projects	62	61	88	69	90
Student Thesis Projects	113	167	226	220	122

Cooperative Research With Air Force Laboratories

One of the requirements for the M.S. and D.Eng.Sc. degrees is satisfactory completion of an independent study on a problem of interest to the Air Force, the results of which are presented as a formal thesis. The only exception is the Aerospace Engineering Program at the Malmstrom Air Force Base branch where advanced graduate course work replaces the independent study.

In five of eleven masters' programs, students devote one to two quarters to cooperative research in one of the Air Force laboratories where they work on problems directly connected with current Air Force research and development programs. In the remaining six masters' programs, the independent study is carried out while taking course work, and the thesis projects are generally sponsored by Air Force laboratories. Whenever possible, faculty research is also sponsored by or closely coordinated with the various research laboratories at Wright-Patterson Air Force Base.

The extent of participation of Air Force laboratories in sponsoring thesis projects of M.S. students at AFIT is shown in the following table.

SPONSORING ORGANIZATIONS

M.S. THESIS PROJECTS

	1962	1963	1964	1965	1966	TOTAL 1962–66
Air Force Institute of Technology	36	45	92	90	60	323
AFIT Nuclear Engineering Test Facility	0	1	0	7	2	10
Aeronautical Systems Division	2	0	3	0	0	5
Aerospace Medical Research Laboratories	1	11	12	8	1	33
Aerospace Research Laboratories	25	41	40	40	24	170
Air Force Aero-Propulsion Laboratory	3	2	3	1	2	11
Air Force Armament Laboratory	0	0	0	1	0	1
Air Force Avionics Laboratory	27	33	18	19	3	100
Air Force Cambridge Research Laboratory	0	0	1	3	2	6
Air Force Flight Dynamics Laboratory	9	11	24	19	17	80
Air Force Materials Laboratory	6	6	12	10	1	35
Air Force Weapons Laboratory	0	1	7	4	3	15
Ballistics Systems Division	0	3	0	0	0	3
Defense Atomic Support Agency	0	0	2	1	0	3
Foreign Technology Division	2	2	2	9	2	17
Missile Development Center	1	0	0	0	0	1
Sandia Corporation	0	0	0	0	1	1
Systems Engineering Group	1	11	6	4	4	26
Wright-Patterson AFB Hospital	0	0	0	2	0	2
TOTAL	113	167	222	218	122	842

faculty

OFFICE OF THE DEAN

Downing, Reginald H., Ph.D., Professor and Dean
Przemieniecki, Janusz S., Ph.D., Professor and Assistant Dean for Research
Hill, John C., Jr., Lt. Col., M.B.A., Assistant Dean

Department of Aeronautical Engineering

Larsen, Harold C., A.E., Professor and Head
Bielkowicz, Peter, Dip. Ing., Professor
Bowman, Robert M., Capt., Ph.D., Assistant Professor
Dickinson, Brian, Sq. Ldr., B.A., Visiting Professor, Royal Air Force
Hayes, Alvin L., Maj., M.S., Associate Professor
Poli, Corrado R., Ph.D., Associate Professor
Van Putte, Ronald E., Capt., M.S., Assistant Professor

Department of Electrical Engineering

Fontana, Robert E., Col., Ph.D., Professor and Head
Brown, Frank M., Maj., Ph.D., Assistant Professor
Burghart, James H., Lt., Ph.D., Assistant Professor
Casey, Kendall F., Capt., Ph.D., Assistant Professor
Chang, Chi Shen, D.Sc., Assistant Professor
D'Azzo, John J., M.S., Associate Professor
Day, Carroll N., Capt., Ph.D., Instructor
Hannen, Russell A., Maj., Ph.D., Associate Professor
Hebborn, Kenneth, Sq. Ldr., B.Sc., Visiting Professor, Royal Air Force
Houpis, Constantine H., M.S., Associate Professor
Johnson, Roger W., Maj., Ph.D., Associate Professor
Kabrisky, Matthew, Ph.D., Associate Professor
Kern, Edward A., Capt., M.S., Assistant Professor
Lubelfeld, Jerzy, Dip. Ing., Associate Professor
Potter, Raymond S., M.S., Associate Professor
Prueher, Roi F., Maj., Ph.D., Assistant Professor
Regulinski, Thaddeus L., M.S., Associate Professor
Schoep, John C., Maj., M.S., Instructor
Zieman, Clayton M., Ph.D., Professor

Department of Humanities

Hand, Harry E., D.Ed., Associate Professor and Head
Davis, Richard M., D.Ed., Associate Professor
Goodman, John S., Lt. Col., Ph.D., Professor
Surratt, I. Webb, M.A., Professor

Department of Mathematics

Carson, Albert B., Ph.D., Professor and Head
Edstrom, Clarence R., M.S., Assistant Professor
Ericksen, Wilhelm S., Ph.D., Professor
Godsey, Neil W., Capt., M.S., Assistant Professor
Harling, Reginald T., M.A., Associate Professor
Holmes, Richard B., Lt., Ph.D., Assistant Professor
Mollo, Robert B., Maj., M.S., Assistant Professor
Moore, Albert H., M.S., Associate Professor
Norris, Donald O., Ph.D., Associate Professor
Persinger, Carl A., Lt., Ph.D., Assistant Professor
Richard, Charles W., Jr., M.S., Associate Professor
Rodstein, Bernard, Lt. Col., M.S., Assistant Professor
Suits, Harlan E., Maj., M.S., Assistant Professor

Department of Mechanical Engineering	Shine, Andrew J., Ph.D., Professor and Head Bahr, William C., Ph.D., Assistant Professor Bulmer, Harry R., M.S., Associate Professor Crossley, Robert W., Capt., Ph.D., Assistant Professor Davis, Hubert, Jr., Capt., M.S., Instructor Eddington, Robert B., Maj., M.S., Assistant Professor Elrod, William C., Ph.D., Associate Professor Franke, Milton E., Ph.D., Associate Professor Hamilton, Leonard A., Lt. Col., Ph.D., Associate Professor Hitchcock, James E., Ph.D., Associate Professor Kepler, Harold B., M.B.A., Associate Professor Wright, Harold E., Ph.D., Associate Professor
Department of Mechanics	Breuer, Delmar W., Ph.D., Professor and Head Anderson, Gerald M., Capt., Ph.D., Assistant Professor Bailey, Cecil D., Lt. Col., Ph.D., Associate Professor Goldberg, William, Capt., Ph.D., Assistant Professor Johnson, Stewart W., Capt., Ph.D., Associate Professor Keister, Paul H., M.S., Associate Professor Kurzenberger, John L., Capt., M.S., Instructor McGetchin, Thomas R., Capt., Sc.M., Instructor Myers, Edward J., Lt. Col., Ph.D., Associate Professor Myers, James R., Ph.D., Associate Professor Torvik, Peter J., Lt., Ph.D., Associate Professor Valey, Valentin A., M.S., Associate Professor
Department of Physics	Pedrotti, Leno S., Ph.D., Professor and Head Battle, Edward L., Lt. Col., Ph.D., Assistant Professor Booth, Ray S., Lt., Ph.D., Assistant Professor Bridgman, Charles J., Ph.D., Associate Professor Evans, Donald L., Lt. Col., M.S., Assistant Professor Freyer, Gustav J., Maj., M.S., Assistant Professor Hengehold, Robert L., Ph.D., Assistant Professor John, George, Ph.D., Associate Professor Kaplan, Bernard, Ph.D., Associate Professor Lewis, LaVerne F., M.S., Professor Replogle, Clyde R., M.S., Assistant Professor Soper, Gordon K., Ph.D., Assistant Professor Wepfer, Gordon G., Capt., Ph.D., Assistant Professor Wilson, John A., M.S., Associate Professor
Department of Systems Management	Dunlap, Lloyd L., Jr., Lt. Col., Ph.D., Associate Professor and Head Cleland, David I., Lt. Col., Ph.D., Associate Professor Conner, Henry H., Jr., Lt. Col., M.B.A., Assistant Professor Enzer, Hermann, Ph.D., Associate Professor King, William R., Lt., Ph.D., Assistant Professor

Minuteman Education Program
Malmstrom Air Force Base
Montana

Kuprenas, Algimantas J., Maj., A.E., Associate Professor and Commander

Air Force Nuclear Engineering Test Facility

Gwynn, Philip S., Col., M.S., Director

FORMER FACULTY 1962-1966

Ackerman, Donald E., Sc.D., Professor of Statistics and Management (1963–66)
Alexander, Shelton S., Capt., Ph.D., Associate Professor of Geophysics (1963–65)
Blakelock, John H., Col., M.S., Associate Professor of Electrical Engineering (1957–65)
Bohannon, James R., Col., M.S., Associate Professor of Physics (1964–66)
Bowman, George P., Jr., Maj., Ph.D., Associate Professor of Chemistry (1961–66)
Bowen, Ray M., Lt., Ph.D., Assistant Professor of Aeronautical Engineering (1961–64)
Bucciarelli, Louis L., Jr., M.E., Assistant Professor of Mechanics (1960–63)
Charette, Franklin M., Maj., M.S., Associate Professor of Mechanics (1961–66)
Cheatham, Daniel W., Maj., Ph.D., Associate Professor of Aeronautical Engineering (1962–66)
Coleman, Jack W., Col., D.B.A., Professor of Accounting (1963–65)
Crouch, Jack G., Lt. Col., M.S., Associate Professor of Aeronautical Engineering and Assistant Dean (1964–67)
Dellinger, David C., Maj., Ph.D., Associate Professor of Statistics and Operations Research (1963–66)
Dolan, Bruce A., Maj., M.S., Assistant Professor of Electrical Engineering (1963–65)
Duemmel, James E., Ph.D., Assistant Professor of Mathematics (1962–64)
Edwards, Prentice D., Ph.D., Professor of Mathematics (1962–63)
Elrod, Bryant D., Lt., Ph.D., Assistant Professor of Electrical Engineering (1963–65)
Goulthorpe, Peter J., Sq. Ldr., M.A., Visiting Professor of Aeronautical Engineering, Royal Air Force (1964–66)
Graetzer, Gunther R., Dip. Ing., Professor of Aeronautical Engineering and Dean Emeritus (1947–65)
Grimes, Charles K., Maj., Ph.D., Associate Professor of Aeronautical Engineering (1963–66)

Hoversten, Estil V., Ph.D., Assistant Professor of Electrical Engineering (1962–65)

Januska, Charles J., Capt., M.S., Assistant Professor of Electrical Engineering (1962–66)

Johnson, James H., M.S., Assistant Professor of Electrical Engineering (1961–63)

Lehmann, William L., Ph.D., Professor of Physics and Assistant Dean for Research (1951–66)

MacCallum, John M., Jr., Maj., Ph.D., Associate Professor of Electrical Engineering (1961–65)

McCormick, James E., Capt., M.S., Instructor in Electrical Engineering (1962–64)

McKenna, William W., Lt. Col., Ph.D., Associate Professor of Mechanical Engineering (1962–66)

Maestri, Raymond R., Capt., M.S., Assistant Professor of Aeronautical Engineering (1960–62)

Mahler, Joseph, M.S., Associate Professor of Mathematics (1963–64)

Martin, Edward P., Capt., M.S., Instructor in Electrical Engineering (1965–66)

Meyfarth, Philip F., Lt., M.E., Assistant Professor of Mechanical Engineering (1961–64)

Minor, Charles B., Maj., M.S., Assistant Professor of Electrical Engineering (1958–62)

Ogar, George W., M.Eng.Sc., Associate Professor of Electrical Engineering (1955–62)

Pratt, Richard L., M.S., Assistant Professor of Mathematics (1960–64)

Pringle, Homer G., Capt., M.S., Assistant Professor of Mechanics (1958–62)

Rausch, Paul J., Lt., Ph.D., Assistant Professor of Metallurgy (1963–65)

Risley, Guy H., Jr., Maj., M.S., Associate Professor of Mechanics (1963–66)

Robison, William C., Lt. Col., M.S., Associate Professor of Mechanical Engineering (1962–66)

Romer, Eugene M., Capt., E.A.A., Associate Professor of Aeronautical Engineering (1960–64)

Saxer, Richard K., Lt. Col., Ph.D., Associate Professor of Metallurgical Engineering (1962–66)

Sharkoff, Eugene G., Lt. Col., Ph.D., Associate Professor of Physics (1963–66)

Smith, Frank R., Ph.D., Professor and Head of Humanities (1953–62)

Stephenson, Orlando W., Jr., Lt. Col., M.S., Associate Professor of Mechanical Engineering and Associate Dean (1958–66)

Synnott, Thomas W., III, Lt., M.A., Assistant Professor of Economics (1961–64)

Tolle, Frederick F., Lt. Col., M.S., Associate Professor of Mechanical Engineering (1962–66)

Tsongas, George A., Lt., M.S., Assistant Professor of Mechanical Engineering (1962–65)

Whicher, William C., Capt., M.S., Assistant Professor of Aeronautical Engineering (1959–63)

Whiting, Carlyle F., Lt. Col., M.S., Assistant Dean of Engineering (1962–64)

Wingerson, Richard C., Maj., Sc.D., Assistant Professor of Physics (1961–64)

Zawalick, Edward J., Maj., M.S., Assistant Professor of Physics (1960–65)

ADJUNCT AND VISITING FACULTY 1962-1966

Adjunct Professors

Theodore E. Cotterman, Ph.D.
Lecturer in Bioengineering
Aerospace Medical Research Laboratories

Stanley J. Czyzak, Brig. Gen., AFRes., D.Sc.
Lecturer in Physics
Ohio State University

Wilbur L. Hankey, Jr., Ph.D.
Lecturer in Mechanical Engineering
Aerospace Research Laboratories

Melvin R. Keller, Lt. Col., M.S.
Lecturer in Physics
Aerospace Research Laboratories

Bernard A. Kulp, Ph.D.
Lecturer in Physics
Aerospace Research Laboratories

Harry A. Lipsitt, Ph.D.
Lecturer in Metallurgy
Aerospace Research Laboratories

Paul D. Lowman, Jr., Ph.D.
Lecturer in Geology
Goddard Space Flight Center

Stuart N. Mapes, Jr., Capt., Ph.D.
Lecturer in Electrical Engineering
Air Force Avionics Laboratory

Erich E. Soehngen, Dip. Ing.
Lecturer in Mechanical Engineering
Aerospace Research Laboratories

Hans J. P. von Ohain, Ph.D.
Lecturer in Mechanical Engineering
Aerospace Research Laboratories

Richard C. Wingerson, Lt. Col., Sc.D.
Lecturer in Physics
Aerospace Research Laboratories

Lynn E. Wolaver, Ph.D.
Lecturer in Mechanics
Aerospace Research Laboratories

Adjunct Lecturers

Richard D. Alberts, B.S.
Lecturer in Electrical Engineering
Air Force Avionics Laboratory

Ronald O. Anderson, M.S.
Lecturer in Electrical Engineering
Air Force Flight Dynamics Laboratory

William J. Anderson, Lt., Ph.D.
Lecturer in Mechanics
Aerospace Research Laboratories

Paul E. Blatt, M.S.
Lecturer in Electrical Engineering
Air Force Flight Dynamics Laboratory

William C. Eppers, Jr., D.Sc.
Lecturer in Electrical Engineering
Air Force Avionics Laboratory

Robert D. Larson, M.S.
Lecturer in Electrical Engineering
Air Force Avionics Laboratory

Robert R. Rankine, Capt., M.S.
Lecturer in Electrical Engineering
Air Force Flight Dynamics Laboratory

Carl A. Traenkle, Dip. Ing.
Lecturer in Physics
Aerospace Research Laboratories

Visiting Lecturers

Howard E. Bethel, Capt., Ph.D.
Lecturer in Mechanical Engineering
Aerospace Research Laboratories

George R. Branner, M.S.
Lecturer in Electrical Engineering
Air Force Avionics Laboratory

Thomas C. Collins, Lt., Ph.D.
Lecturer in Physics
Aerospace Research Laboratories

Chauncey H. Dean, Litt.M.
Lecturer in Accounting
School of Systems and Logistics, AFIT

Charles E. Dugan, M.S.
Lecturer in Management
Ohio State University

Kenneth H. Griffin, B.Sc.
Lecturer in Aircraft Structures
College of Aeronautics, England

Edward W. Hess, Maj., M.B.A.
Lecturer in Research Management
Aeronautical Systems Division

William T. Johnson, Jr., Maj., M.E.
Lecturer in Mechanics
Civil Engineering Center, AFIT

Marshall Kreitman, M.S.
Lecturer in Physics
Aerospace Research Laboratories

Horace W. Lanford, Col., Ph.D.
Lecturer in Management
Aeronautical Systems Division

David A. Lee, Lt., Ph.D.
Lecturer in Physics
Aerospace Research Laboratories

Kanakanahalli S. Nagaraja, M.S.
Lecturer in Aeronautical Engineering
Aerospace Research Laboratories

Leon J. Radziemski, Lt., Ph.D.
Lecturer in Physics
Aerospace Research Laboratories

David G. Roddy, Ph.D.
Lecturer in Astrogeology
U.S. Geological Survey
California Institute of Technology

Donn G. Shankland, Ph.D.
Lecturer in Physics
Aerospace Research Laboratories

Ian E. Smith, Ph.D.
Lecturer in Propulsion
College of Aeronautics, England

Walter P. Sory, M.A.
Lecturer in Russian
University of Dayton

John J. Spillman, D.C.Ae.
Lecturer in Aerodynamics
College of Aeronautics, England

George H, Springer, Sc.M.
Lecturer in Geology
University of Dayton

Richard L. Stanley, J.D.
Lecturer in Contract Law
School of Systems and Logistics, AFIT

Robert L. Swaim, Ph.D.
Lecturer in Electrical Engineering
Air Force Flight Dynamics Laboratory

Douglas R. Talcott, Ph.D.
Lecturer in Behavioral Science
Research Technology Division

Cyril K. Trotman, B.Sc.
Lecturer in Aircraft Design
College of Aeronautics, England

Helmut Weik, Ph.D.
Lecturer in Physics
University of Cincinnati

aeronautical engineering

H. C. LARSEN

Head, Department of Aeronautical Engineering

During the period 1962–66, the faculty members of the Department of Aeronautical Engineering have been engaged in a wide range of research activities encompassing both theoretical and experimental investigations in fluid mechanics and the design and operation of different types of aerospace vehicles.

The fluid mechanics research covered such dissimilar fluids as generalized continua, discrete molecules, perfect gases, plasmas, viscous liquids, and the atmospheres of various planets. Methods of analysis ranged from pure and applied mathematics to experimentation in wind tunnels, shock tubes, plasma generators, and flow simulators.

Other research activities included work on conventional and novel aircraft, missiles, rockets, satellites, interplanetary spaceships, "hedge-hopping" ground-effect machines, and rifle bullets. These studies covered many aspects, such as analysis of requirements, preliminary through detail design, optimization, modification, testing (both wind-tunnel and actual-flight), and operational tactics.

The following sections describe some of the research in the Department.

Mathematical Analyses

A number of purely mathematical investigations have been undertaken by faculty members to develop the mathematical tools necessary for solving problems in fluid mechanics.

In one such investigation an iterative procedure for finding arbitrary roots of numbers was employed. Much work has also been done on numerical methods and recursion formulas for solving boundary-value problems arising in fluid flow and continuum mechanics.

Several faculty members have been studying the application of tensor analysis to problems in fluid mechanics. Furthermore, the calculus of variations has been applied to obtain solutions to problems in aeronautics and optimization studies.

Non-Ideal Fluids

Various theoretical studies in plasma, microwave diagnostics, and infra-red spectroscopy have been undertaken. An example of these studies is the analysis of Prandtl-Meyer flow with a transverse magnetic field.

The Department teaches advanced courses in molecular flow and kinetic theory, and much of the material used in these courses originated from faculty research projects on rarefied gases and real gas effects.

The relationships among viscosity, compressibility, and heat conduction in fluids have been investigated both theoretically and experimentally. For example, an investigation carried out to determine the interaction between shock waves and boundary layers in shock tubes produced evidence that plane shock waves are much less stable than was previously predicted.

Flow Visualization

One of the major interests of the Department is the development of methods by which fluid flow can be presented visually to students, thus allowing for a better understanding of the phenomena being discussed in class. The Department has maintained two smoke tunnels for this purpose. More recently, however, faculty and student research projects have resulted in the development of a new way of demonstrating the laws of fluid flow. The traditional Hele-Shaw technique has been extended to simulate potential flow with sources, sinks, and circulation (see Figs. 1–3). Another device for demonstrating two-dimensional flows is the electronic analog whereby a cathode ray tube is used to simulate supersonic flow, shock waves, and rarefaction waves. Construction of this analog in the Department is being investigated theoretically.

Three-dimensional flow visualization has been obtained in wind-tunnel oil-streak studies. In particular, one student used this method to show the pattern of flow over a cone at various angles of attack in a low-speed flow. The possibility of using holographic techniques for three-dimensional flow visualization is presently under study.

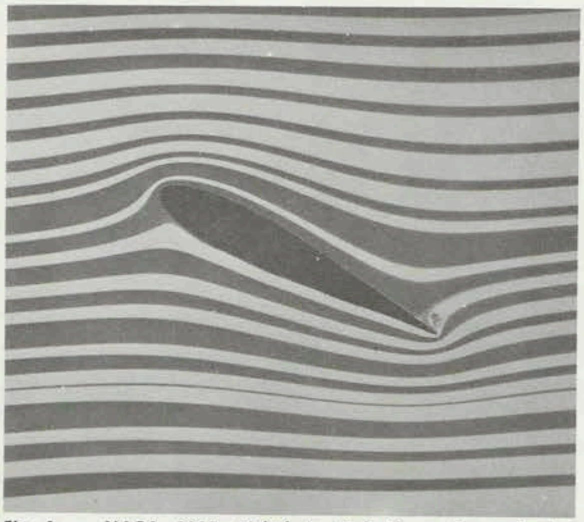


Fig. 1 NACA 0015 airfoil in Hele-Shaw flow showing potential flow without circulation. Stagnation points are visible on upper surface near trailing edge and on lower surface near leading edge. Width of streamtubes is inversely proportional to local velocity. The airfoil is a solid obstacle.

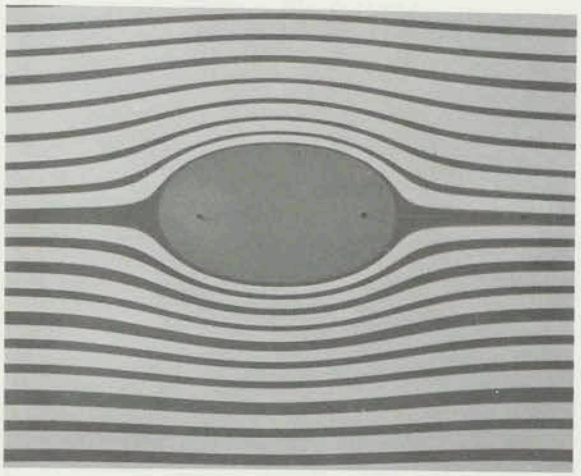


Fig. 2 Rankine body in Hele-Shaw flow formed by source and sink at the two dark spots. Fluid is streaming out of the upstream hole and is pumped out of the downstream hole. The intermediate gray color is fluid from the source and is not a solid obstacle.

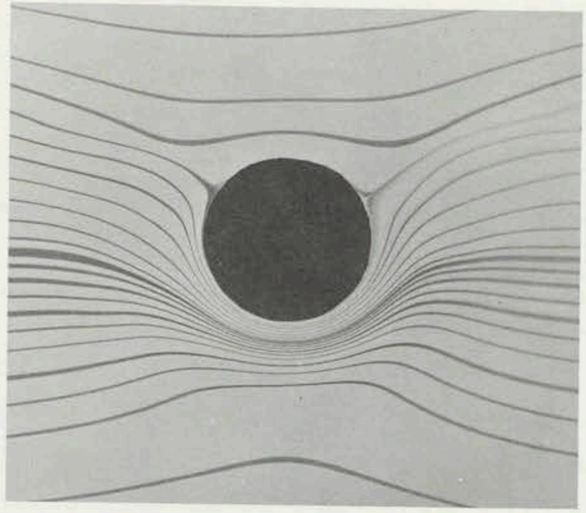


Fig. 3 An attempt to create circulation in a Hele-Shaw flow by contouring the width of the channel between the plates. While not the true flow, it indicates how the Hele-Shaw flow can be modified to illustrate circulation.

Vehicle Design and Test

A method of preliminary design using generalized performance parameters has been developed. This technique has been successful in the design of various aerospace vehicles, the most prominent of which is the counterinsurgency aircraft (see Fig. 4). This aircraft incorporates the results of a great many student thesis projects on various components. One of the most important features of this aircraft is the blowing flap, a concept proved to be feasible by tests in the AFIT 5′ x 5′ wind tunnel.

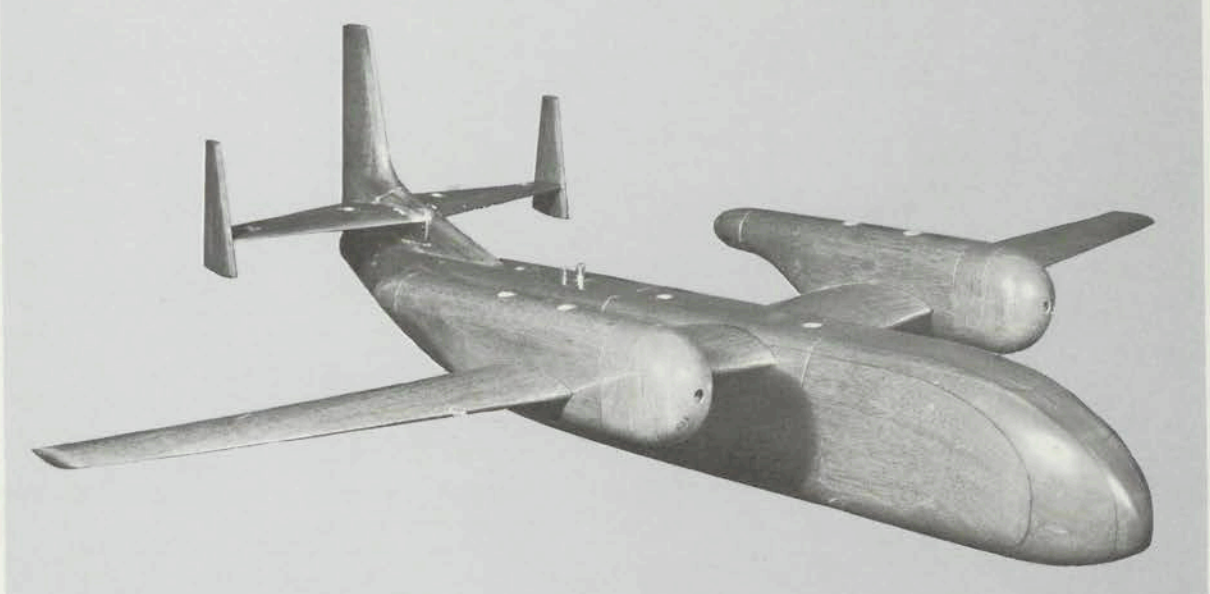
In another design study, a ground-effect machine capable of operating at some distance from the surface for short periods of time was considered. The "hedge-hopping" capability of this vehicle is particularly attractive and warrants further development. A model of this design is currently being tested in the wind tunnel.

Another design that involved considerable research and development work was the Air-Launched Air-Recovered Rocket (ALARR) air sampler. This design was the result of a detailed theoretical study, followed by wind-tunnel and flight testing, and it was developed into an actual hardware (see Fig. 5). Various faculty members have also been active in the design of interplanetary vehicles, their structures, propulsion systems, crew stations, and ground-support equipment.

Some research has also been undertaken in the general field of atmospheric re-entry; and various configurations, such as balloons, the Rogallo para-wing, and sails, have been investigated both theoretically and experimentally.

A great many wind-tunnel studies have been completed on the low-speed characteristics of aerospace vehicles, including tests to determine landing characteristics of delta-wing bodies, lifting bodies, variable sweep vehicles, the Dyna-Soar, and the Wright Aeronautical Development Division Configuration II (WADD-II). The Department's low-speed wind tunnels have also proved invaluable in determining characteristics of nonaerodynamic shapes when being towed by an aircraft or a helicopter. Faculty research in this area has led to the successful modification of space capsules to allow them to be towed without damaging the supporting vehicle.

Fig. 4 A counterinsurgency aircraft designed by AFIT and tested for performance, stability, and control characteristics.



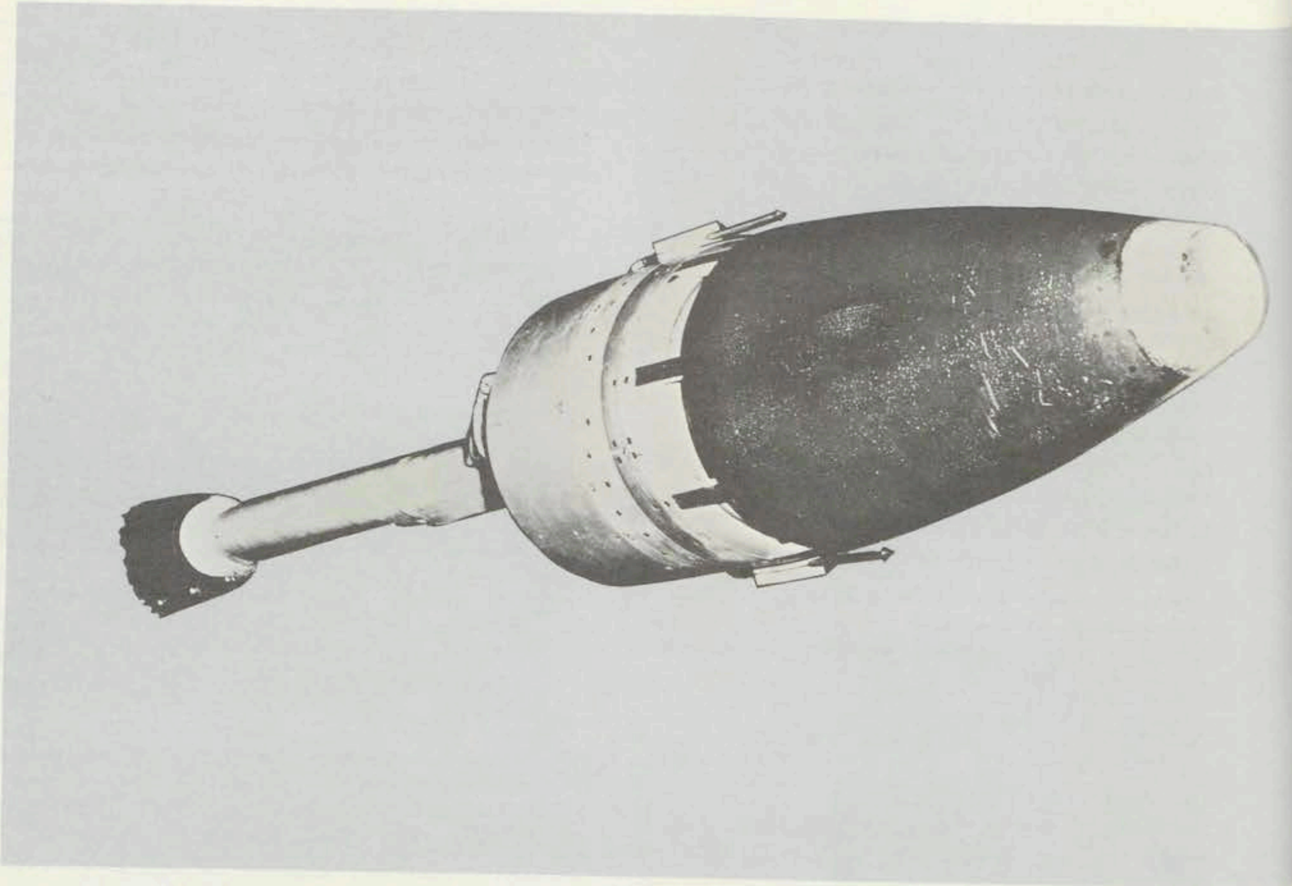


Fig. 5 A high-altitude supersonic filter-paper air-sampler designed by AFIT and tested in the Arnold Engineering Development Center's 16' supersonic wind tunnel. Successful operation at M=2 and above 210,000 feet altitude has been achieved.

Most of the Department's wind-tunnel investigations have come about as a result of a direct request from some government agency needing low-speed data. Practically every government agency involved in the design or use of vehicles in the atmosphere has at one time or another requested and received assistance from AFIT wind-tunnel facilities.

Vehicle Performance, Stability, and Control

Performance optimization has been the subject of several thesis projects. In these studies, vehicle configuration, thrust scheduling, pilot technique, and flight-path scheduling have been analyzed to obtain minimum take-off distance, minimum time-to-climb, and maximum range. Some studies have been made to analyze the effect of unusual configurations, such as the canard, variable sweep, and reflexed ailerons, and to assess the stability of aircraft that incorporate these elements in their design.

The generalized performance technique of preliminary design mentioned previously has led to the adaption of the digital computer to aircraft performance and stability calculations. Some of the work in stability and control of unconventional-configuration aircraft has been verified by radio-controlled models built in the Department (see Fig. 6).

Vehicle Tactics and Operations

The counterinsurgency aircraft designed in the Department was optimized by judging its performance in the particular type of tactical mission peculiar to counterinsurgency operations. First, the mission had to be determined. The various types of air missions to be performed by such an aircraft include reconnaissance, strike, reconnaissance-strike, command and control, and light/utility transport. To ensure that the designed aircraft had the required capabilities in the anticipated geographical and meteorological environment, a detailed study was made of the aircraft's performance, handling qualities, reliability, flexibility, survivability, and attack effectiveness. The final design showed great promise.

In the analysis of space vehicle performance, various mission profiles have been investigated. These include satellite and missile interception and evasion techniques, astronaut retrieval techniques, and landing techniques for various planetary atmospheres and surfaces.

Space

The effect of man's movements within and around the space vehicle on the orbital motion has been analyzed. This analysis included the effect of elastic deformation of the vehicle.

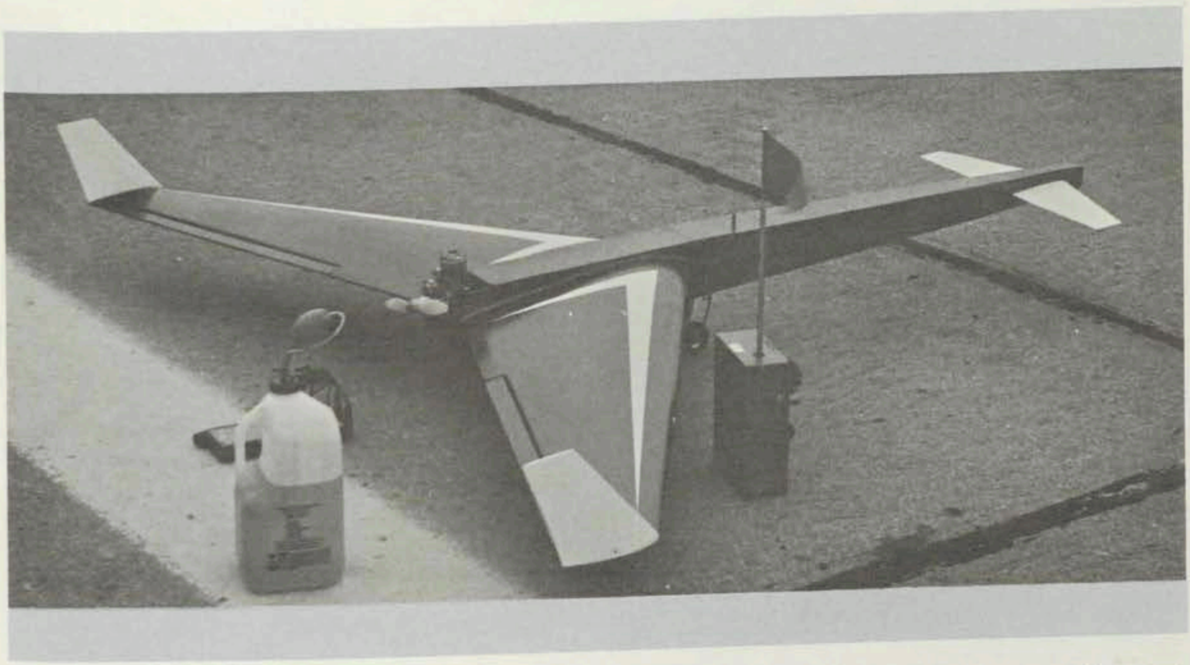


Fig. 6 Radio-controlled canard model built to demonstrate techniques which were developed in a stability and control course offered by the Department of Aeronautical Engineering.

Ground Tracks of Synchronous Satellites

P. BIELKOWICZ
Professor of Aerospace Engineering

The ground track of a satellite is the trace on the surface of a planet described by the radius vector joining the satellite to the center of the planet. On a nonrotating planet, this trace is an arc of a great circle and is fully defined by the inclination i of the orbit with respect to the equatorial plane. This inclination defines the maximum latitude attained on the trace. On a rotating planet, the shape of the track depends on the angular velocity of the planetary axial rotation and on the parameters of the orbit i, e, ω, p, where i is the inclination, e the eccentricity, ω the longitude of the perigee, and p the period of sidereal revolution (see Fig. 7).

A special family of orbits is that of synchronous satellites, whose periods are equal to that of the planet; for the earth period p=23 hours 56.07 minutes. Such satellite, if injected into a circular orbit in the equatorial plane of a planet, would remain stationary with respect to the surface of the planet, and its track would then be reduced to a point.

If, however, we increase the eccentricity and inclination of the orbit and vary the location of the perigee for an elliptical orbit, its track will become a closed curve whose shape and size depend on the selected set of parameters i, e, ω. This curve is repeated on successive orbits if the orbital perturbations are neglected. In some cases, this curve resembles the figure eight.

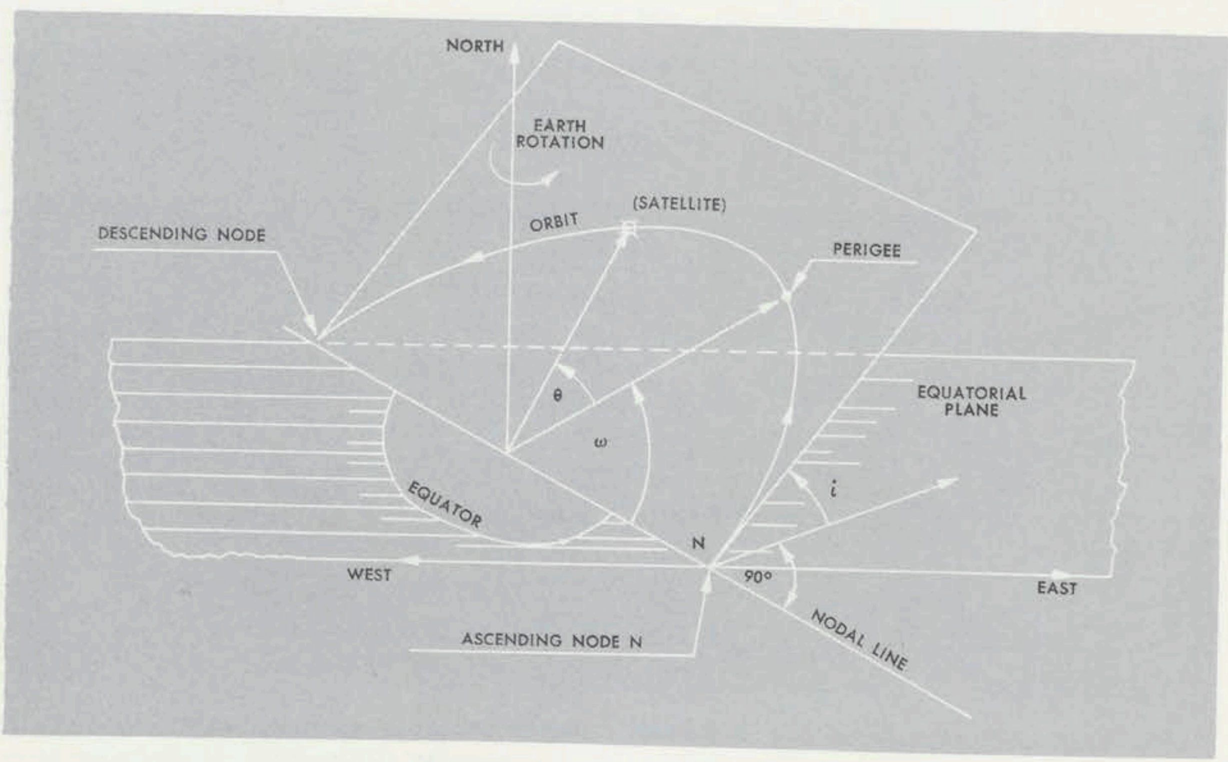


Fig. 7 Orbital parameters.

In 1964 a request was received from the Air University Warfare Systems School, Maxwell Air Force Base, to investigate some particular tracks of the earth-period satellites. Although the tracks of synchronous satellites on the earth's surface were previously investigated, full treatment of this subject did not exist in published literature. The study performed at AFIT was an attempt to obtain a full analysis of the problem and to compute a few typical tracks.

The following results were obtained:

• For certain ranges of perigee location, the typical figure eight disappears entirely. The track becomes a simple closed curve of rather large amplitude.

• By properly combining i, ω, and e, it is possible to produce a very small loop in the track in which the satellite will spend a considerable fraction of its period, hovering for 4–6 hours near the zenith of a selected locality with an amplitude of 2°– 6°. This important finding is of value for observation and communication satellites, and it enables us to conduct continuous observations and telecommunications.

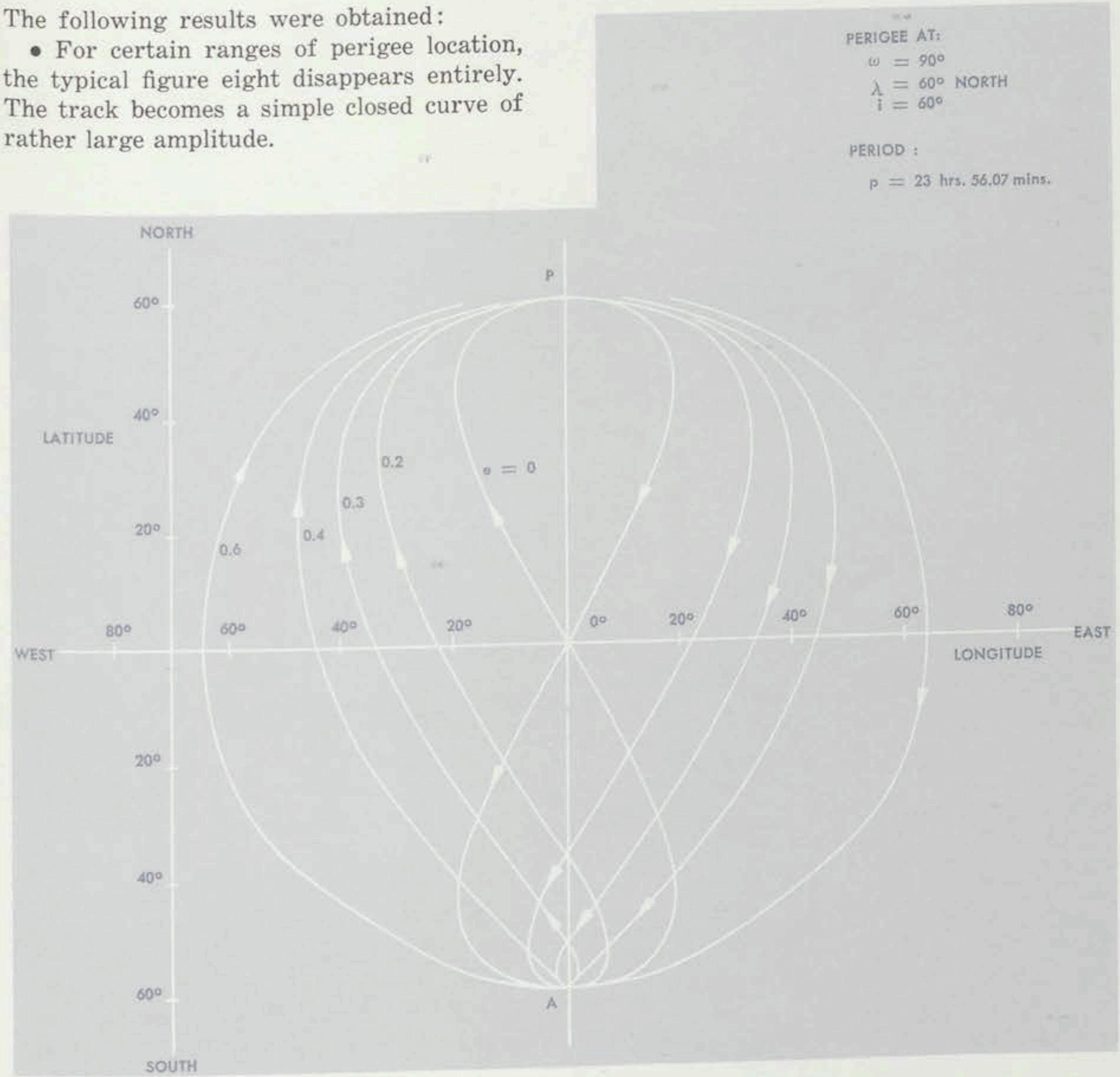


Fig. 8 Satellite tracks for various values of eccentricity e.

• The amplitudes of tracks in the investigated examples have been found to be much wider than those previously estimated for the same values of the orbital parameters. These results are illustrated in Figs. 8 and 9. Figure 8 shows the variation of the track of a synchronous satellite's orbit having fixed inclination and perigee location for different values of eccentricity. The perigee for all tracks is at the point P, and the apogee is at A. The symmetrical figure eight for $e=0$ represents the track of a circular orbit. The lower loop grows smaller with the increasing eccentricity and finally disappears. In Fig. 9, the origin is taken at the ascending node, and the inclination i and the eccentricity e are fixed; the variable parameter is the longitude ω of the perigee.

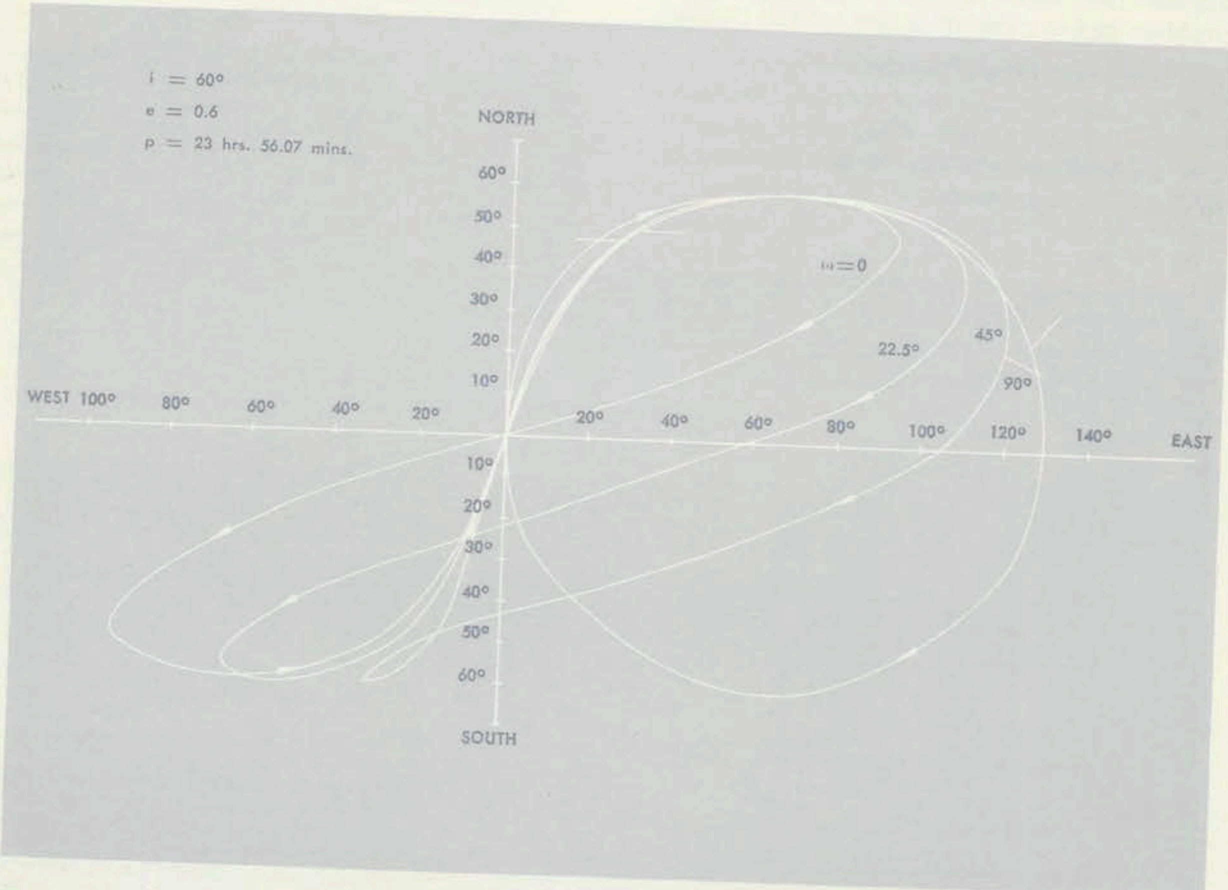


Fig. 9 Satellite tracks for various values of perigee location ω.

The completed study concerns only a satellite in a restricted case of an ideal spherical earth. The oblateness of the planet will produce the perturbations of the orbit. Because of the long stay of the satellite at the latitude where the small loop is located, these perturbations will be magnified by resonance effect. A study is now in progress to investigate these perturbations.

electrical engineering

R. E. FONTANA, *Colonel, USAF*
Head, Department of Electrical Engineering

The major study and research areas included in the Department of Electrical Engineering are centered around two broad categories: automatic guidance and control; and electronics, including communication and information processing. The automatic guidance and control program emphasizes both aerodynamic flight and astronautical regimes; the electronics program includes sequences in electromagnetics, communication-information theory, system modeling, computer theory, bioengineering, and molecular electronics. Research efforts in these areas have been greatly enhanced by the excellent facilities available at the Wright-Patterson Air Force Base laboratories. These facilities are available for faculty and student research, which is conducted in close collaboration with laboratory scientists. Under this cooperative effort, academic discipline and research have become inseparable components of the graduate program.

Aerospace Guidance and Control

Automatic guidance and control encompasses several disciplines within the engineering regime. Although it draws heavily from the study of control theory, the solutions for the problems generated by the guidance and control of aerospace vehicles require detailed knowledge of current propulsion and aerodynamic limitations coupled with a thorough familiarity with astrodynamic trajectory theory. This Department was among the first to recognize the importance of such a program and to implement a formal curriculum designed to prepare Air Force officers for important assignments in aerospace guidance and control.

A number of research projects have been carried out on control methods for space vehicles. In one project a modified gravity gradient attitude control system was investigated. A bi-metallic strip was used to provide momentum exchange in this investigation. Digital simulation indicated that this modified system had superior performance to the classical gravity gradient method. Another project employed moment gyros and self-organizing controllers to stabilize a satellite under disturbance inputs up to and including 375 ft-lb. This work was carried out in conjunction with the Flight Dynamics Laboratory, Wright-Patterson Air Force Base, and extensive analog simulations produced a 600 per cent improvement over existing attitude controllers. Another investigation in this area showed that geomagnetic forces acting on a satellite do not provide adequate torque for attitude control.

The synthesis of controllers for various trajectory applications has also been investigated. Using both numerical and analytical techniques, libration point studies were undertaken. A significant reduction of amplitude in the oscillations of a small body around the restricted three-body libration point was found through the proper selection of initial conditions and the choice of the satellite injection time relative to the sun's position. The range of parameters identified reduced peak amplitudes and divergence rates by 70 and 75 per cent, respectively. It was determined that the sun's perturbation produces ultimate instability at the libration point (i.e., earth recapture of a 100-lb. satellite within approximately four years). Periodic orbits were then synthesized in a cislunar model (four-body). This digital simulation was accomplished in conjunction with the Aerospace Research Laboratories, Wright-Patterson Air Force Base.

In the guidance area, a research project considered a two-point boundary value optimal control problem using analog simulation. Human operators were used to adjust initial conditions and control parameters in a boost-rendezvous application. The purpose of this investigation was to determine response characteristics with human operators in the loop and to gain insight into the effective parameters of a human operator. The analog facility of the Flight Dynamics Laboratory was used extensively for this simulation. Another project investigated the use of an inertial guidance unit to control injection into a transfer orbit to rendezvous with a satellite. Good performance was demonstrated by digital simulation for reasonably short interceptions. Research on the synthesis of a discrete optimal controller for an entry vehicle established the criterion for optimization as a quadratic function of the guidance constants of each possible control point along the entry trajectory. Assuming a desired terminal point, nominal optimal entry trajectories were found which were least susceptible to disturbance, initial condition, and guidance errors. Using an approximate form of the discrete controller with a Chebyshev norm for a typical entry mission, a closed-loop linear guidance law was derived. The approximate feature of the controller is desirable to facilitate relatively simple calculations in an on-board computer so that steering commands are computable in the short intervals between control points. Such a system is desirable for post-Apollo missions where recovery is planned at fixed landing sites.

Research in the aeronautical control area included the design and analyses of attitude stabilization systems for aircraft in the present and projected Air Force inventory. An extensive analysis of the lateral control channel of the B–58 aircraft evaluated the aileron rate limitation to preclude stick lock-up while landing in gusty winds. The results provided greater confidence in the system design. Another research investigation evaluated the use of a fixed-gain controller to augment the lateral control channel. This method was deemed unsatisfactory because of negligible response to rudder control during engine failure. Otherwise, performance was good; the yaw damping coefficient ζ was increased to a range of $0.28 \leq \zeta \leq 0.56$ from $0.02 \leq \zeta \leq 0.16$ and pilot coupling was eliminated. Another method employed a limit-cycle adaptive gain concept. A compensator was designed and implemented into the lateral channel which set the limit-cycle to 10 rad/sec. This method was not considered completely satisfactory because of a low damping condition in the "Dutch roll" mode. The results of this work, coupled with extensive simulations conducted at the Flight Dynamics Laboratory, pointed the way to ultimately designing an effective lateral controller for the B–58 aircraft.

In another project, the Minneapolis-Honeywell self-adaptive system (MH–96) was compared with a linear high-gain system for controlling the short-period pitch dynamics of the X–15. This analysis proved that the linear-high-gain system was preferable to the self-adaptive one. Since the yaw-orientation system shows severe limitations in effectively controlling the longitudinal mode of the X–15 during the entire descent from 100,000 ft., a controller was also synthesized and proved feasible for controlling the terminal phase of a return from space. Further research considering application to the supersonic transport control problem confirmed that an adaptive control system, employing the parameter perturbation technique, was superior to an adaptive system employing the limit-cycle self-adaptive concept in the minimization of gust disturbances.

A significant contribution in the inertial navigation area was related directly to the Air Force's effort to develop a no-gimbal or strap-down inertial navigation system. Initially a 43 per cent reduction in position uncertainty was shown for such a system employing external velocity information obtained from aerial photographs. Adaptive control techniques were applied to increase and control the damping of the system, and the results showed the adaptive system to be superior to a constant damped system. Of six methods of computing the attitude matrix employed in a strap-down inertial navigation system, a second-order direct algorithm followed by a first-order sequential algorithm was found to be the most satisfactory. The Flight Dynamics Laboratory has provided strong support to this Department's research efforts on aerodynamic systems.

Electromagnetic Theory

The Department research efforts in electromagnetic theory have been conducted in close cooperation with Base laboratory facilities. In many cases they represent contributions to the Air Force research programs directed by these laboratories. One such example is the design, construction, and study of a metal tube Argon II laser performed under the sponsorship of the Laser Branch, Air Force Avionics Laboratory, Wright-Patterson Air Force Base. The argon ion laser is capable of very high power outputs in continuous operation; however, a cooling problem exists. The cooling problem was overcome by constructing the laser with copper discs of high thermal conductivity and viton 0-rings stacked alternately—a design that resulted in one of the first successful lasers of this type (see Fig. 1).

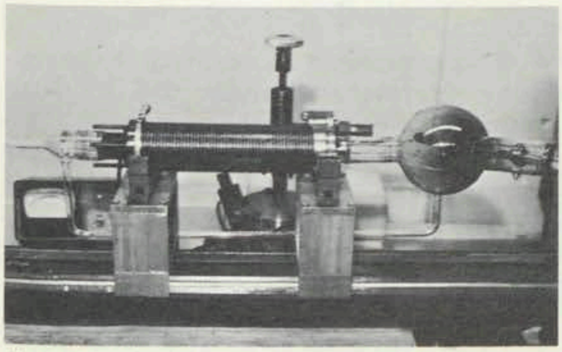


Fig. 1 Complete laser assembly

A study sponsored by the Antenna Radome Group, Air Force Avionics Laboratory, investigated various techniques for measuring the dielectric constants of materials at elevated temperatures. The result of this study was a modified technique which involved a computer program to calculate the dielectric constant and the loss tangent of radome materials at elevated temperatures.

Research involving a computer approach to laser design was conducted in support of the Weapons Guidance Laboratory, Aeronautical Systems Division. The problem of maximizing laser efficiency is usually accomplished empirically and requires the construction of a number of devices. Under this concept, equations relating subefficiencies to measurable parameters were used as a basis for a model for which a computer program was prepared. In this manner, a good approximation to optimum design can be obtained before actual physical construction of the system.

An important contribution to the technology of microwave measurements involved the extension of the nodal shift technique for measuring scattering parameters of microwave n-ports. The accuracy of the usual slotted line technique for measuring these parameters is limited by the calibration of the voltage standing wave ratio (VSWR) meter and the degree to which the terminating impedances approach a perfect match. These sources of inaccuracies are removed in the Weissfloch-Feinberg nodal shift technique which involves a short-circuit termination and the measurement of deep node positions. Unfortunately, this technique has been limited to 2-ports. Under the AFIT program, the nodal shift technique was extended to arbitrary lossless n-ports by reducing it to a sequence of lossy 2-port problems. This unique approach allows the calculation of scattering parameters of a lossless n-port without the need for matched loads or field-intensity measurements.

Statistical Communication Theory

Research in statistical communication theory has proceeded in part with the cooperation of the Applied Mathematics Laboratory, Aerospace Research Laboratories. This effort has been directed toward the determination of the response of certain nonlinear systems to random-process excitation. The van der Pol, the modified van der Pol, and Duffing equations have been simulated using Gaussian noise of known spectral density. The autocorrelation functions and power spectra of the outputs were then found. A significant result of this study has been the effect of the nonlinearity parameters on noise suppression in these nonlinear systems.

In another study, design criteria were established for use in USAF contract specifications for FM systems operating on strictly band-limited channels. The distortion introduced into FM signals by a band-limited channel was derived and simulated for several input signals. Also, an investigation of error probabilities in a non-Gaussian channel was completed. This study considered coherent amplitude- and phase-shift keyed digital systems in the presence of additive Beckman noise or "atmospheric noise." A computer program yielding error probabilities for any signal-to-noise ratio and an arbitrarily large alphabet were written and used to compare the behavior of the system with another system operating in the usual Gaussian environment. It was found that the Gaussian model yielded predicted probabilities of error that were quite optimistic in comparison with those predicted by the more realistic model.

Systems Modeling

A system may be defined as a collection of interacting diverse human and machine elements integrated to achieve a common desired objective by the control of materials, information, energy, and humans. To be able to study a phenomenon mathematically or experimentally, it is necessary to formulate the mathematical or physical equivalent. This constitutes the essence of modeling. When the study is directed at a system, the formulation is then referred to as systems modeling.

Most of the research in systems modeling has been focused on reliability, maintainability, and safety, and has included a number of projects sponsored by Air Force laboratories and other Department of Defense agencies. A typical example of this effort is the research undertaken in the area of reliability prediction through systems functions. Under investigation was the feasibility of reliability prognosis of communication systems as a function of such parameters as bandwidth, noise figure, power output, and modulation indices. On the basis of the results of this study, which yielded a number of positive indicants, the Air Force Systems Command, the sponsor of this research, requested that AFIT continue the studies in modeling reliability as a function of power output and modulation modes.

In 1964 a research grant was received from the Defense Atomic Support Agency (DASA) to study the feasibility of a six-channel multiplex and telemetry transmitter design in connection with DASA research in fallout-particle sizing. The reliability modeling of the proposed design was started the following year and included reliability allocation and prediction based on a minimum specified mean time between failure and maximum flight mission time. The research culminated in a report entitled "Reliability Prediction Study of Telemetry Multiplexer and Transmitter," in which it was demonstrated that a design to withstand nuclear environment within the specified time constraint is possible.

The reliability characteristics of selected complex communication networks, and the use of flow graphs in a reliability analysis of systems have also been investigated. These resulted in the development of lattice and bridge configuration reliability functions suitable for computer processing, and for a proposed Markov model appropriate to the solution of a multimoded system in which the state and transitional probabilities of moving from one mode to another are of interest.

A number of programs sponsored by Air Force laboratories were focused primarily on the reliability analysis of conventional and molecular circuitry. One research program evaluated the variation in output parameters of LC type vacuum tube and transistor feedback oscillators as a function of integrant manufacturing variation. The distribution of output frequency was determined by a statistical analysis of computer-generated random samples in order to ascertain which oscillator configurations were inherently the most reliable. A related effort evaluated selected multivibrator vacuum tube and transistor circuits. In this evaluation, pulse characteristics were investigated, and aging was simulated by permitting integrant parameters to drift with time. As a result of this program, degradation was determined to be a function of circuit configuration, and selection criteria were established.

Reliability research on molecular circuitry led to the investigation of performance variation of an integrated circuit chip as a function of temperature. The Legendre method of regression used on the experimentally obtained data yielded the underlying mathematical model which governed the relationship between the input conditions and bandwidth, phase shift, and voltage output. This in turn made possible the use of computer simulation techniques to generate a joint frequency distribution from which performance prediction could be obtained.

A study in human performance reliability modeling has been undertaken jointly with the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base. The aim of this study is to investigate, from an underlying error-rate probability density function, the feasibility of modeling the reliability of human task performance. The immediate goal, following the design of a human experiment, is to have subjects perform a typical Air Force operational task in a simulated environment. The data collected will show the occurrence of errors in relation to both time of error and trial number. The processing of data will include the examination of a number of density functions—Beta, Weibull, Gamma, exponential—to determine which functions describe the distribution of errors.

A study of systems safety modeling was sponsored by the Directorate of Nuclear Safety, Kirtland Air Force Base, New Mexico. The study involved the development of models that would accurately reflect the inadvertent launch of a nuclear weapon system. Current research includes the formulation of the various contributory events modeled from system and subsystem functional configurations, where the input for each model is obtained from the subsystem failure prediction. The ultimate objective of this research is to establish safety criteria for the weapon system under consideration.

Computer Design

Main areas of computer theory research have included residue arithmetic, threshold logic, noise sensitivity in self-organizing machines, and optimal state-assignment. Only the research in residue arithmetic is discussed in this report.

Residue arithmetic was first described in 1957 by Svoboda of the Czechoslovak Academy of Sciences. A number N is represented in this system by a sequence $(r_1(N), r_2(N), \ldots, r_k(N))$ of residues of N with respect to a sequence $(m_1, m_2, \ldots, m_k)$ of fixed moduli; the j^{th} residue $r_j(N)$ is the remainder after division of N by the j^{th} modulus m_j. An important property of the residue number system is that the residue representations of the sum and product are computed without having to deal with a *carry* of any kind. These operations may therefore be mechanized in a computer in such a way as to consume only one operating cycle rather than the hundreds of cycles ordinarily required. Under the research program in residue arithmetic, a small relay computer, whose input and output were in the (3, 4, 5) residue system, was constructed. Since this computer had no memory unit, it effectively demonstrated the instantaneous nature of calculations in the residue number system. Two other devices, a residue-to-mixed-radix converter and a polynomial evaluator, were also designed. The residue number system has serious limitations in overflow detection, sign detection, and division. These problems are all related to the difficulty of converting a residue number to its weighted (binary, octal, decimal, etc.) equivalent. The residue-to-decimal conversion problem was investigated as part of a related AFIT effort in residual arithmetic, and the principles developed were incorporated in a (3, 4, 5) relay converter. The complexity of the conversion problem is indicated by the fact that the converter—output appendage — was far more complex and required much more ingenuity than the computer to which it was attached. Another investigation on analog-to-residue conversion established that an intimate relation exists between the apparently disparate topics of residue numbers and verniers. The consequences of this relation were developed in detail and applied to the general problem of converting analog measurements into their residue equivalents. The Air Force Avionics Laboratory has used this work as the basis for more extensive research on analog-to-residue conversion.

Bioengineering

Bioengineering is the discipline that applies the techniques of engineering to biological problems. In 1961, the Department of Electrical Engineering began work on the problem of determining how an animal's nervous system processes sensory information concerning the animal's environment. Information theory, the starting point for this investigation, is an important engineering subject in its own right, and in the bioengineering context offers a powerful technique to aid in determining how animals process data. Clues provided by animal nervous systems suggest new ways to fabricate information-handling systems for specific technological needs.

One of the problems studied concerns the mechanism of human vision. How do human beings recognize the common everyday things despite variations in the position and size of the retinal image? Although seemingly a trivial question because the task is so commonplace, the computing operation performed by the brain to accomplish visual recognition is of such complexity as to be little understood. Results of this study have led to some useful hypotheses, and have shown that known neural structures can perform pertinent operations on two-dimensional images such as cross-correlation and Fourier transformation, which are useful for certain visual recognition functions.

Another bioengineering problem that has been extensively studied is that of blood-flow dynamics. The mechanisms that regulate blood flow, particularly in weightless environments, are not well understood. In 1962, a renal physiologist joined the faculty and, with groups of students and a faculty committee on bioengineering, began studying the specific problem of the automatic regulation of blood flow through the kidney and its effect on system blood pressure. The group has developed a mathematical model of kidney behavior and has constructed a mechanical-hydraulic analog model of the kidney which duplicates all of the important blood flow regulation mechanisms known to be performed by the kidney. Animal experiments to verify the flow-pressure profiles predicted for the living kidney by this model are now being performed, and these results are being prepared for publication. An interesting by-product of this research is an invention by one of the members of the group of a new type of pressure-regulator valve, based on kidney function, which should be of great value to the Air Force.

In another project, the ability of humans to perform mechanical tasks in weightless and lunar gravity environments was investigated. This problem was approached in two ways: (1) by using the unique facilities of the zero-*g* aircraft provided by the Aerospace Medical Research Laboratory, a mathematical model of the mechanical structure of the human body was derived and verified; and (2) by using control system theory, the analysis of human kinesthetic behavior was studied. The sensors and actuators in human skeleton-muscle systems are known, but their behavior is little understood. They are highly nonlinear, and have dead-zone and hysteresis defects, yet they can provide elegant adaptive control that in many important respects cannot be matched by manmade systems. The Aerospace Medical Research Laboratory has developed extensive electromechanical analogs of animal feedback-control systems including the neural control circuitry. Through their use, the following AFIT projects were conducted: the throughput characteristics of rabbit leg musculature; the transfer characteristics of position and tension transducers in muscles and tendons; and the determination of models of complete position-tension servosystems based on animal analogs.

The exposure to reduced and zero gravity is a relatively new experience for man; much speculation has occurred concerning the effects of these environments on the otolith apparatus in the inner ear and the neural information-processing networks associated with maintenance of equilibrium and sense of direction. There is little doubt that receptors exist in the vestibular apparatus that can detect the direction and magnitude of the gravity vector (and therefore linear acceleration) with respect to the head, and that these receptors are most likely the otolith organs. Research at AFIT was undertaken to obtain a description of the otolith organ portion of the vestibular system.

The eyeball counterroll response to a rotation of the head about the visual axis was used as the output detector of the behavior of the otolith system. (With the use of a mirror, the reader can observe this counterroll response by rotating his head about an axis perpendicular to the mirror while observing blood vessels in the white of his eye used as reference marks to show eye position.) This method was used because of the inherent difficulties of directly investigating an organ located completely within the solid bone of the skull behind the ear and because previous research has shown that eyeball counterroll is one external manifestation of vestibular system response.

A special rotation device for human subjects was constructed by AFIT students, with the support of the Aerospace Medical Research Laboratory, in which rotation up to 30 rpm about the visual axis could be obtained (see Fig. 2). The counterroll behavior was measured by a special photographic process developed for these experiments, which enabled comparison of the eye under counterroll with the eye photographed at rest. As a result of these experiments, counterroll quantitative dependence as a function of lateral head tilt and angular velocity was determined for the first time, and a mathematical description of the transfer characteristics of the human otolith system was derived. These experiments are being continued with monkeys. Using animal subjects, it is possible to selectively alter, by surgical procedures, selected portions of the vestibular and neural apparatus, and thereby develop a more accurate description of the system.

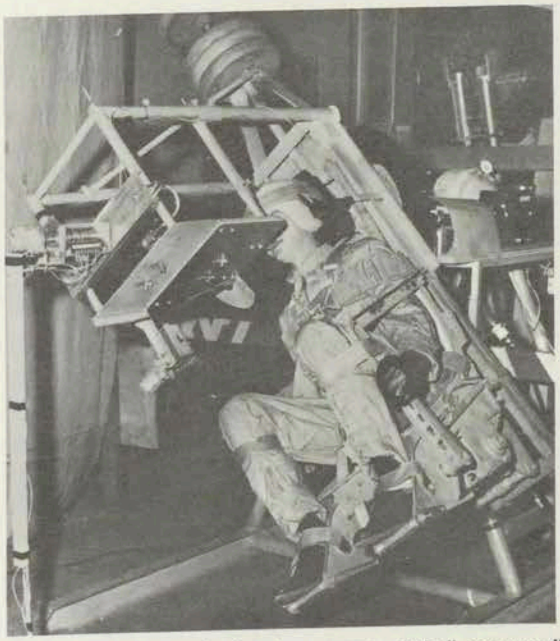


Fig. 2 Rotation mechanism to measure eyeball counterroll in human subjects.

Molecular Electronics

A cooperative Electronic Materials Laboratory is under development and, when completed, will permit an expansion of the research effort of students and faculty. Some typical examples of research in molecular electronics conducted at AFIT are described in the following paragraphs.

In a continuing project sponsored by the Air Force Avionics Laboratory, the properties of a plasma generated by photoelectric processes are being investigated. Most of the present plasma microwave devices use plasma generated by either hot-contact surface ionization or collision between an electron beam and a neutral gas. Since the design of a device based on a photo-plasma requires a better understanding of the electron energy distribution in such a plasma, the project is being conducted to determine this distribution. Another project sponsored by the Avionics Laboratory involved experimental and theoretical investigations associated with the development of electroluminescent panels that can be used for video displays. A part of this program was the fabrication and testing of a number of crossed-grid display elements employing nonlinear resistant, photoconductive, and electroluminescent layers. The results have served as inputs to the continuing effort in this area.

The different modes of interaction between electromagnetic radiation and matter are important in numerous communication engineering, medical electronics, and industrial electronics applications. A research project was sponsored by the Navigation and Guidance Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, to investigate one form of this interaction, namely the second harmonic generation in triglycine sulphate. Several lasers were used as primary radiation sources. Through an exchange of ideas and material support, encouragement for this project was given by the University of Michigan, Science Laboratory of the Ford Motor Company, Atomic Physics Section of the National Bureau of Standards, Illinois Institute of Technology, and The Ohio State University Research Foundation. A significant finding of this work was temperature dependence of second-harmonic generation.

An investigation of a laser interferometer attitude monitoring device represented the first angle-sensing application of the interference principle and the coherent nature of the laser beam. The system was analyzed, designed, built, and tested, and was found to have highly satisfactory performance. The work was sponsored by the Advanced Methods Branch of the Guidance and Control Division of Holloman Air Force Base, New Mexico.

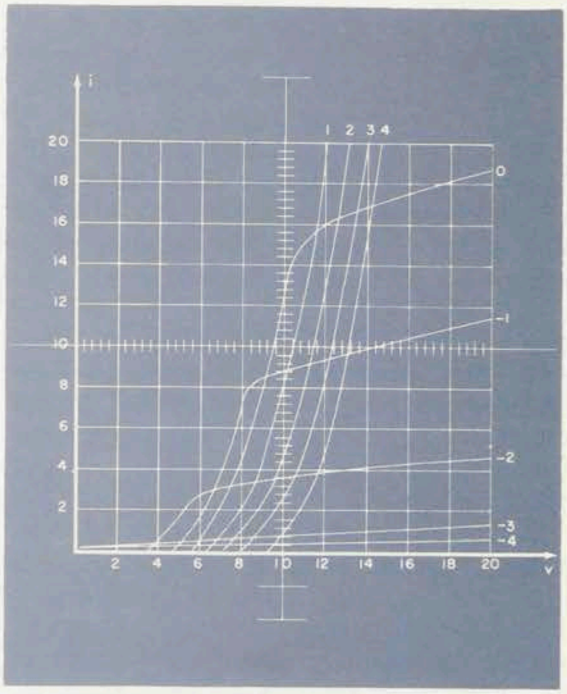


Fig. 3 Static v-i characteristics of a composite MOS device of a higher complementarity order. "Double points" are formed when there are two controlling voltages for a given v-i.

The physics of surfaces has been exploited empirically in a considerable number of thin-film devices. However, the theory is incomplete and one of the main difficulties encountered results from the charge-trapping phenomenon. There are several mechanisms involved, but exoelectron emission is probably unavoidably associated with various methods of thin-film fabrication. A project was undertaken for the Electronics Research Branch, Air Force Avionics Laboratory, to determine the dependence of trapping on film thickness, and to measure exoemission during the fabrication processes. The results had higher accuracy than those obtained previously and should provide a basis for a better understanding of the fundamental processes involved.

Among the high-frequency properties of compound semiconductors, the Gunn effect is of great interest since it may lead to the design of an extremely compact, lightweight, simple (no discrete components), solid-state Klystron. A contribution to the understanding of these properties was made as a result of an experimental investigation of current-limiting and oscillation in cadmium sulphide. Under this program, sponsored by the Aerospace Research Laboratories, several devices were fabricated and tested.

In addition to complementarity of composite surface field-effect devices (MOS), which is based on opposite charge species, it has been found that these devices also offer a complementarity which is based on opposite modes of conduction control (enhancement and depletion). Under an AFIT research project sponsored by the Air Force Avionics Laboratory, it has been shown that higher order complementarity devices display static volt-ampere (v-i) characteristics with "double points" (see Fig. 3). This property suggests that a variety of electronic functions may be performed by the same physical circuit. Such a versatility will permit more efficient use of thin-film integrated circuits.

An Application of an Analog Computer to Solve the Two-Point Boundary-Value Problem for a Fourth-Order Optimal Control Problem

R. A. HANNEN, *Major, USAF*
Associate Professor of Electrical Engineering

In this study the utility of an analog computer and a human operator was investigated for solving high-order optimal control problems in which Pontryagin's Maximum Principle can be applied. The primary purpose was to aid in the development of efficient techniques that can be applied to the solution of a large class of nonlinear two-point boundary-value problems. As an illustration of the utility of the analog computer-human operator technique, the time-optimal space-rendezvous of a target vehicle in a fixed circular orbit and a maneuvering vehicle in the same orbit plane was considered.

The maneuvering vehicle has bounds on rocket thrust and fuel. The equations of motion for the maneuvering vehicle are written in terms of a uniformly rotating two-dimensional rectangular coordinate system with its origin fixed to the target. The coordinate system, with axes x and y, has a constant angular velocity ω with respect to an inertially fixed coordinate system. The equations of motion are

$$\ddot{x} - 2\omega\dot{y} = A(t)\cos\Phi(t) \qquad (1)$$

$$\ddot{y} + 2\omega\dot{x} - 3\omega^2 y = A(t)\sin\Phi(t) \qquad (2)$$

where $\Phi(t)$ is the steering angle and $A(t)$ is the magnitude of the thrust. The cost function is

$$J = \int_0^{t_f} (1 + \lambda A(t))\,dt \qquad (3)$$

where λ is a Lagrangian multiplier. Further, the thrust $A(t)$ is subject to

$$0 \leq A(t) \leq A_{max} \qquad (4)$$

$$\frac{m_o}{c}\int_0^{t_f} A(t)\,dt \leq m_{po} \qquad (5)$$

where

A_{max} = max acceleration (constant)
m_{po} = initial mass of fuel
m_o = total mass of vehicle (constant)
c = rocket effective exhaust velocity

The application of Pontryagin's Maximum Principle to this problem results in a two-point boundary-value problem. Most methods for solving this problem have employed a trial-and-error approach in choosing the initial conditions on the adjoint equations such that boundary conditions of the state equations are satisfied.

The two-point boundary–value problem was solved on an analog computer. The functional block diagram of the simulation is shown in Fig. 4 The analog computer system also included a display on two variplotters of the $\dot{x}x$ and $\dot{y}y$ phase planes of the admissible trajectories. When the value of $\dot{x}$ or x changed sign, a relay was energized by the operator to switch the computer to *hold*. The operator could then observe the errors of both phase planes and correct the adjoint initial conditions accordingly until on successive runs the phase plane trajectories reached their respective origin at the same time.

It was found that if a separate pot were used for each of the four adjoint initial conditions, solutions were very difficult to achieve. Thus, several dependent schemes of arranging the initial condition potentiometers were tried. The scheme depicted in Fig. 4 was most successful in decoupling the effect of pot adjustments on the two phase planes. Using this scheme, less than five minutes was needed to obtain trajectories which come very close to the origins of both phase planes.

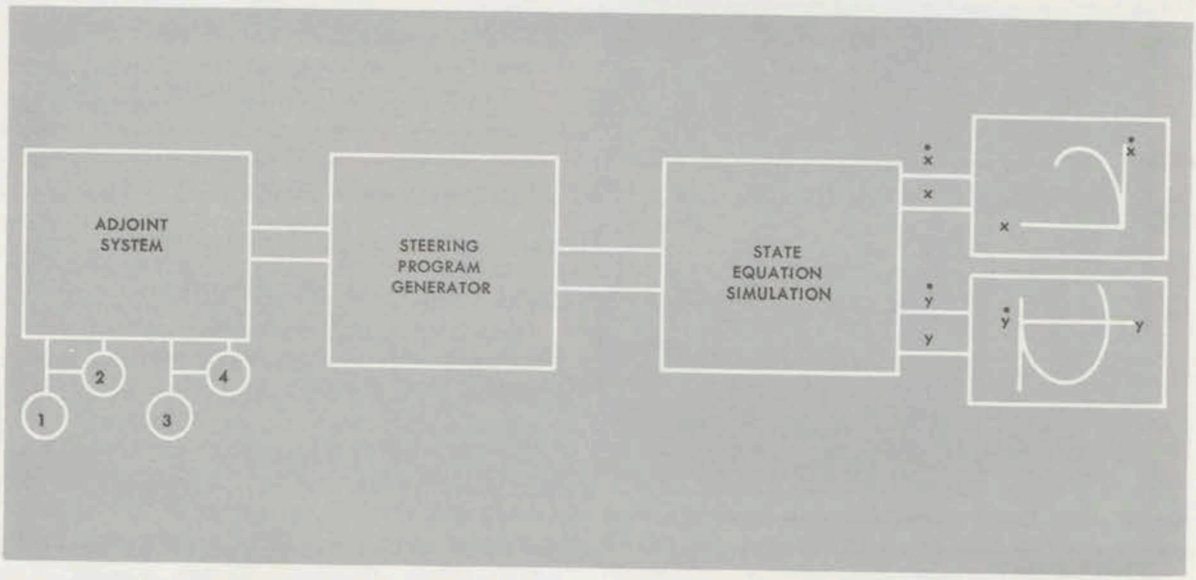


Fig. 4 Functional block diagram for simulation of a two-point boundary-value problem.

The rendezvous problem was solved for several sets of initial conditions and with various weighting factors on time and fuel. The solutions were compared with the solution of the same problem using MIMIC. Considering the MIMIC solutions as exact, the control laws determined by the analog computer contained very little error. Thus, if analog accuracy is acceptable, the analog computer can be used to solve a large class of two-point boundary-value problems.

A Generalized Linear Guidance Law for Aerospace Vehicles

R. W. JOHNSON, *Major, USAF*
Associate Professor of Electrical Engineering

The implementation of optimal controls described by such authors as Breakwell, Kelly, and Bryson can be instrumented in many ways into an effective control law for dynamical systems of the two-point boundary-value (TPBV) vintage. The important factor in the selection of the *order* of the control law required is centered in the expected magnitude of the errors which the process must control. If the expected level of errors is small, a linear control law may be adequate. On the other hand, if the errors are larger than the specified linear controllable region (i.e., when linear sensitivity terms no longer predict an accurate steering command), then a second- or third-order law is mandatory. The step to a higher-order system is a difficult one. For this reason, a linear guidance law will be investigated for a dynamical system described mathematically by a set of nonlinear ordinary differential equations and a set of initial- and final-state conditions. The neighboring optimal control method typifies a procedure that will yield an optimal control for a TPBV problem coupled with the control variations needed to implement a linear guidance law. The neighboring optimal method was used in an AFIT project to describe an innovation to handle disturbance errors more effectively.

The neighboring optimal method has previously been discussed by several authors from various viewpoints. These discussions assume that the deviations from the nominal trajectory are made by comparing the actual state $x(t)$ and the nominal state $x^*(t)$ in the interval $t_0 \leq t \leq t_f$ at a corresponding time. It is unfortunate that the monotonic function of time is used as the index for comparison because, in general, neighboring optimal trajectories have different time intervals. As a result, when a deviation $\delta x(t)$ exists at t_1, for example, $[\delta x(t_1) = x(t_1) - x^*(t_1)]$ the value of the feedback gain factor is selected from the stored nominal values on the basis of the value of time t_1. Since the time interval on the particular neighboring trajectory does not coincide with the nominal trajectory value, an error resulting from the time difference is introduced.

A new approach was considered at AFIT to remove the disturbance errors propagated by this time difference, thus yielding a more effective generalized linear control law for the general dynamical system already described. The control law is relatively easy to mechanize as it directly affects the source of the error. Since the independent variable time is causing the difficulty in this problem, a different monotonic function is needed as the independent variable. The definition of this independent variable must include the mandatory property that its value for the nominal trajectory be the same as that of all neighboring optimal trajectories; thus, it will remove the error-producing effect rather than merely compensate for it.

The entry example considered in this investigation was a drag modulation optimal control to produce a given acceleration profile. An effective method of identification and discrimination of the main payload of a ballistic missile from its accompanying decoy pattern is to observe the initial deceleration profile. The payload will yield a typical profile for its constant ballistic coefficient while the decoys will deviate from this profile because their parameters cannot easily be made the same as the principal payload unless, of course, equal mass is allocated to each decoy. This property suggests that through drag modulation the deceleration profile of the main payload could be made to look like a typical decoy or vice versa.

Considering a zero-lift, planar entry formulation, the equations of motion using the state vector representation is made for positional radius x_1, velocity magnitude x_2, and radial velocity x_3. It is desired to select an optimal control $u^*(t)$, $t_o \leq t \leq t_f$, to produce a given deceleration profile requiring minimization of the criterion functional

$$J(\min) = \int_{t_o}^{t_f} \left[\frac{dx_2}{dt} - \left(\frac{dx_2}{dt} \right)_d \right]^2 dt \quad (1)$$

The variations of control with the dependent variables can be determined directly from the entry equations of motion and the optimal control. Hence,

$$\nabla u^*(t) = \left(\frac{\partial u^*}{\partial x_1}, \frac{\partial u^*}{\partial x_2}, \frac{\partial u^*}{\partial x_3} \right) \quad (2)$$

If time is used as the integration variable, each value of $u^*(t)$ and $\nabla u^*(t)$ is known at the index of time. As indicated previously, the time intervals of neighboring optimal trajectories are different; thus, a new monotonic index is needed for comparing the nominal and neighboring optimal trajectories. The function or surface (function of existing dependent variables), which satisfies the constraint that its value for the nominal be the same as that of all neighboring optimal trajectories, is range angle x_4.

Since the entry equations are usually written with time as the independent variable (i.e., dx_1/dt, dx_2/dt, dx_3/dt), the independent variable is shifted to range angle when the entry equations are divided by dx_4/dt. The integration step-size of range angle is then used as the independent variable to integrate, in general, the nonlinear differential equations to produce the nominal trajectory $x^*(x_4)$. The feedback gain coefficients are, in general, by-products of the neighboring optimal method and are computed at each surface point since the independent integration variable is range angle x_4. The criterion functional of Eq. (1) takes the equivalent form, $J(\min) =$

$$\int_{x_4^o}^{x_4^f} \left[\frac{dx_2}{dx_4} - \left(\frac{dx_2}{dx_4} \right)_d \right]^2 \left(\frac{dx_4}{dt} \right) dx_4 \quad (3)$$

The linear optimal closed-loop control law is thus derived in a form which eliminates the errors resulting from the different time intervals between neighboring optimal trajectories.

To evaluate the merits of this innovation, the entry equations were programmed on a digital computer for both time and range angle as the independent variable. The nominal trajectory for each variable was generated along with the optimal control and feedback gain coefficients. Using the optimum control and feedback gain coefficients for time and range angle as indices, a guidance law was simulated on the digital computer for various perturbations in initial velocity. The performance was then evaluated for the two optimal criteria functionals [Eqs. (1) and (3)]. The comparison of performance is shown in Fig. 5, which indicates the remarkable increase of the controllable region for the range angle as the independent variable.

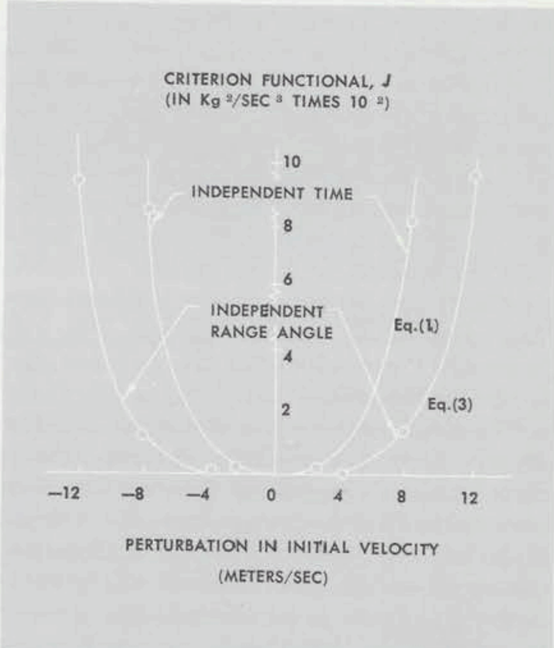


Fig. 5 Criterion functional J vs. initial perturbations of velocity.

The final boundary-value condition for range angle is a requirement for this TPBV problem; thus, it is selected as the independent variable. This satisfies the selection criteria mentioned earlier.

The integration interval of each computer program is carefully adjusted so that computer round-off and truncation errors are equal. This ensures that the comparison of criterion functionals in Fig. 5 reflects that a proper choice of an independent variable will actually improve the performance of a linear guidance law.

The innovation of modifying the index of a linear guidance law to one that yields the same value for nominal and neighboring optimal trajectories is shown to extend the linear controllable region of a linear guidance law. It is felt that this concept leads to a more generalized linear guidance law. The drag modulation control used in the example for a ballistic entry vehicle is analogous to derivative control and, as such, shows promise for making identification and discrimination of the main payload of a ballistic missile more difficult.

Visual Information Processing in the Human Brain

M. KABRISKY
Associate Professor of Electrical Engineering

Since 1961 a continuing research project has been directed toward the problem of understanding the information-processing techniques used by animal nervous systems. One of the main interests in this study was visual pattern recognition. The visual system may be regarded as an information processing computer whose variables are two-dimensional patterns imaged on the retina. With such inputs, the system computes the nature and status of its environment in order to determine appropriate behavior. It is a curious fact that, even as possessor's of such a system, we understand very little of its internal operation. It is important, however, to study both animal and human visual systems so that we may

(1) understand fully their special abilities and shortcomings in order to use them most effectively in artificial environments, such as aircraft or spacecraft cockpits, and

(2) copy, with man-made equipment, some of their unique and as yet unreproduced capabilities, such as the ability to recognize familiar objects invariant to position, rotation, and scale changes.

Taking clues from structures known to exist in the human visual system, a mathematical model of human visual function based on cross-correlation of two-dimensional input images with stored images has been developed. This model has demonstrated how recognition of visual objects invariant to position, scale change, and moderate rotation and local distortion could be obtained in the human brain. The model predicted the existence of the fundamental neural information processing components in mammalian cortex—components which were subsequently discovered in animal experiments by other investigators. The most important result was the demonstration of how actual neural circuits could perform the kind of computations necessary in performing the visual pattern recognition function. Some of the key results of this work have been published in a series of papers in a book entitled *A Proposed Model for Visual Information Processing in the Human Brain.*

At present, a more efficient implementation of the computer simulation of the model is being set up at the Aerospace Medical Research Laboratories (AMRL), Wright-Patterson Air Force Base. In order to speed up test simulations and performance evaluation of the model while allowing for parameter adjustments, a special optical apparatus, permitting direct optical input to a medium-sized digital computer (PDP–1) was built. The results of the model's computation, as simulated on the PDP–1, can be displayed directly on a cathode ray oscilloscope. Thus, it will be possible to insert two-dimensional test patterns into the system and observe immediately the results of the model's behavior. Heretofore, lengthy punched-card-input procedures required by conventional computer installations have impeded this investigation. The new system is expected to be operational in March 1967.

With the aid of computer programmers at AMRL, another portion of this investigation is being conducted to simulate epilepsy-type instabilities in the model. Epilepsy is a brain disorder characterized by widespread oscillatory disturbances in the information-processing centers of the brain. The model of the brain functions developed to simulate the behavior of the brain as an information-processing device can, when improperly adjusted, manifest oscillatory disturbances which behave very much like natural epilepsy. The parameter changes required to produce this aberrant behavior in the model are remarkably small and are being quantitatively analyzed to determine if any meaningful clues to human epilepsy may be derived from the model's behavior.

A third portion of this investigation, conducted with the assistance of AFIT M.S. students, concerns the most efficient way to store information in systems modeled after animal brains. The data used by the brain are not the numbers and symbols used in the contemporary computer, but are models, in some homolog form, of the set of objects and concepts pertinent to living in this three-dimensional, time-varying world. How to efficiently store such data in a brain is a problem that has been solved by evolution but not by man. Recently, however, we have shown how to store information in a distributed form, using models based on known neural structures. The memory system we have developed (based on Fourier-hologram transformation) uses very little storage space to store two-dimensional images; the images are not seriously degraded even if substantial parts of the stored, transformed image are destroyed. In addition, such a memory gradually fades in time in a noisy environment but always retains remnants of the original image. These are known to be salient characteristics of animal memories. The system is intrinsically oriented to the storage of two-dimensional patterns and would be quite useless as the memory organ of a machine designed to handle numbers in a precise way. Work on this problem is continuing and may provide interesting insight into actual brain function as well as clues to build useful hardware for automatic pattern recognition systems.

A Computer Approach to Laser Design

J. LUBELFELD
Associate Professor of Electrical Engineering

The problem of maximizing laser efficiency is usually approached through experimental study. The method developed in a study conducted at AFIT permits us to approximate the optimum design before actual physical construction of the system. This method is based on the idea that under a set of simplifying yet realistic assumptions, the efficiency of a four-level laser may be considered as a product of six subefficiencies. Each of these subefficiencies is associated with one of the loss mechanisms operative in the system. The set of equations which relates these subefficiencies to physically measurable parameters constitutes the model for system overall efficiency.

Using this mathematical model, a program was written for the 1620 IBM computer. A sample problem involving the design of a neodymium-doped glass laser oscillator was solved to illustrate the use of the model. The flexibility of the method was demonstrated by optimizing the variables with respect to output energy rather than efficiency, and by introducing the possibility of maintaining a safety factor to ensure the achievement of threshold. The results obtained were in general agreement with known theoretical and experimental properties of the pulsed four-level laser, and this fact lends support to the validity of the model.

In general, it can be said that, within the limitations imposed by the assumptions and approximations used in the development of the model, the system efficiency will (1) increase as the laser rod length is increased, (2) increase as the laser rod radius is increased, (3) increase as the doping density is increased, (4) decrease as the end reflectivities are increased, (5) increase as the pumping energy is increased, and (6) decrease as the pumping pulse decay time constant is increased.

No attempt was made to make the model applicable to CW operation of the four-level laser, or to the so-called pulsed reflector and hair-trigger modes of operation. It is believed, however, that the basic mathematical development is applicable to all of these conditions and that only minor changes in the computer program would be necessary to represent them by the model.

An Equivalent Gain and Stochastic Analysis for Nonlinear Sampled-Data Systems

R. F. PRUEHER, Jr., *Major, USAF*
Assistant Professor of Electrical Engineering

The analysis and design of automatic sampled-data feedback control systems, in which an element operates in a nonlinear mode, are often accomplished by means of an equivalent linearization of the nonlinear element. This linearization is usually done by means of techniques developed by Chow and Kuo. In both methods, the equivalent linearization of the nonlinear element is defined as the ratio of an output signal to an assumed sinusoidal input signal. As such, these techniques apply to that class of systems which operates with a single, deterministic, sinusoidal actuating signal. This analysis cannot handle systems with multi-input and stochastic-input signals.

In a study conducted at AFIT a more general definition for the equivalent linearization of a nonlinear element in a sampled-data system has been proposed and demonstrated for a few specific cases. This general definition has the following advantages:

- It is applicable to the multiple input cases.
- It can be used with either deterministic-input or stochastic-input signals.
- The results of Chow and Kuo are special cases of this more general definition.
- It is applicable to both autonomous and non-autonomous systems.

Note that in the basic definition, there are no restrictions placed upon either the input or output signals. They can be random, stationary, ergodic, deterministic, or any combination of these signal types. However, if the input signals are restricted to certain types, the computation of the Equivalent Gain Function can be simplified. In addition, the zero-order hold (ZOH) data reconstruction device is a low-pass filter element which provides the required smoothing of the higher-order harmonics generated by the nonlinear element.

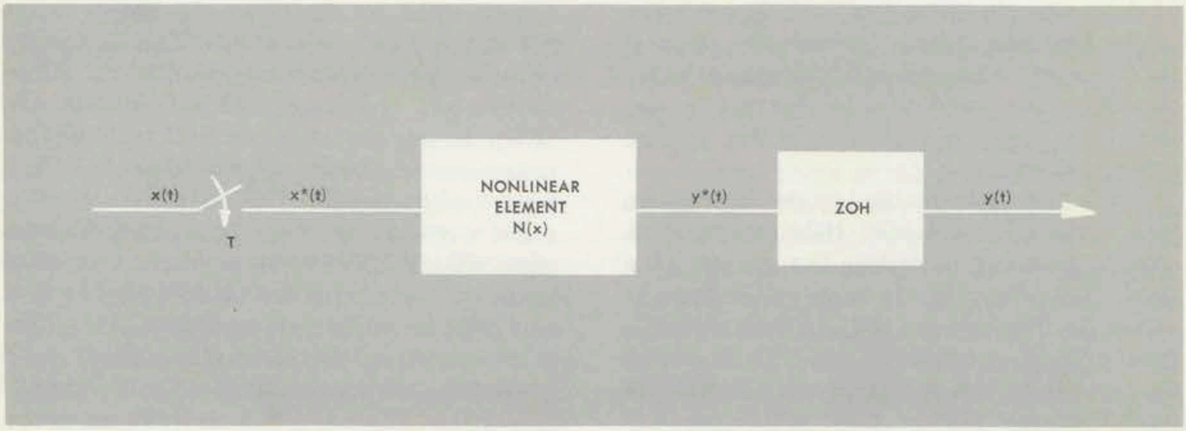


Fig. 6 Nonlinear element.

In order to define the Equivalent Gain Function $K_{eq}(z)$, consider an isolated, single-valued, time invariant element $N(x)$ which has zero memory and possesses odd symmetry. This element is subjected to an input signal $x(t)$ and yields an output signal $y(t)$ as shown in Fig. 6. The equivalent gain is then defined to be the ratio of the z-transform of the cross-correlation function of a given input signal and the output signal divided by the autocorrelation of the input signal. Thus

$$K_{eq}(z) = \frac{\Phi_{xy}(z)}{\Phi_{xx}(z)} \qquad (1)$$

Once the requisite $K_{eq}(z)$ has been found for any specific input, it can be substituted for the nonlinear element $N(e)$ in the system shown in Fig. 7. The resulting system is now a linearized control system and the subsequent analysis can be carried out by using the linear techniques developed by Kuo or Johnson. When such an analysis is performed, the magnitude and phase of the actuating signal $e(t) = E \cos(\omega_o t + \phi)$ can be predicted to a high degree of accuracy.

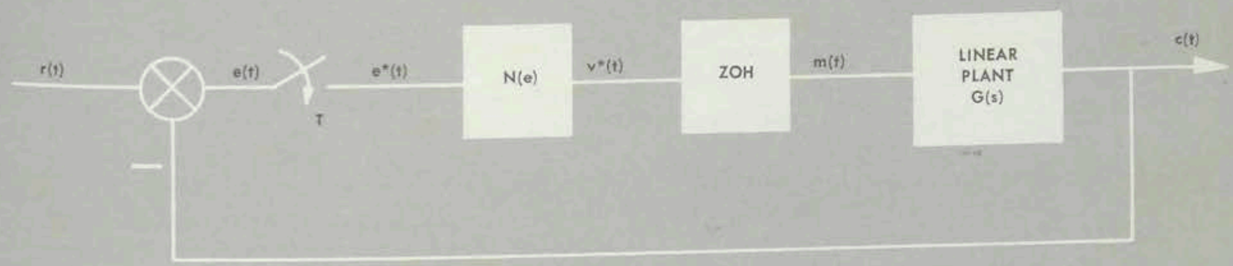


Fig. 7 Nonlinear sampled-data system.

In order to illustrate the application of the definition of the Equivalent Gain Function to an actual system, an analog and digital computer study has been performed on the system shown in Fig. 7. Here $G(s)=\frac{k}{s(s+1)}$ and the nonlinearity is a dead-zone relay as shown in Fig. 8. In order to provide a comparison between the use of the ensemble and time-averaging methods of computing the correlation functions, a sinusoidal input given by $r(t)=A\cos(\omega_0 t+\theta)$ was selected. The deterministic form is as given above and the stochastic description can be given by the density function which is

$$p(\mathrm{x})=\frac{1}{\pi\sqrt{A^2-x^2}} \quad \text{for } -A \leqq x \leqq A \qquad (2)$$

and $t'=t+\tau$. For these conditions, the Equivalent Gain Function was found to be the same for both input signal descriptions and is given by

$$K_{eq}(z)=\frac{2\sqrt{2}}{\pi}\frac{B}{A}\left[\frac{z}{z\cos\phi-\sin\phi}\right] \qquad (3)$$

This function was substituted for $N(x)$ in the system shown in Fig. 7 and a linear analysis furnished the following results

$$E = 1.685 \qquad (4)$$
$$\phi = -6^\circ\ 33'$$

A digital computer solution was performed and the results were

$$E = 1.697 \qquad (5)$$
$$\phi = -6.52^\circ$$

In addition, the actual and equivalent systems were run on Model 1631–R analog computer, manufactured by Electronics Associates, Inc. Although some of the internal signals were not the same, the system output signals agreed closely. In fact, the differences between $e(t)$ and $c(t)$ for the actual and equivalent systems were so small that these signals were almost identical.

Several examples of an input signal at the plant frequency have been run on the analog computer. In order to illustrate the use of the Equivalent Gain Function for a multiple input, the system shown in Fig. 7 was subjected to an input signal consisting of one component at the plant frequency and another at the third harmonic. This yields a more complex expression given by

$$K_{eq}(z) = \frac{\frac{3BE}{2\pi}\cos\phi - \frac{\sqrt{3}BE}{2\pi}(\sqrt{3}+j1)\sin\phi + \frac{2AB}{3\pi}}{\frac{1}{2}\left(\frac{3}{2}E^2+A\right)} \qquad (6)$$

Substituting this function for $N(x)$, the equivalent system has been shown to furnish a very good representation for $e(t)$ and $c(t)$.

As before, some internal signal discrepancies are present, but they do not seriously affect the output because of the smoothing effects of the ZOH and linear plant.

Two types of the final random input signal were used: (1) Gaussian noise and (2) Gaussian noise through a linear filter. For these cases, the Equivalent Gain Function becomes

$$K_{eq}(z) = \sqrt{\frac{2}{\pi}}\left(\frac{B}{\sigma}\right) e^{-b^2/2\sigma^2} \qquad (7)$$

This system was also simulated on the analog computer and the results were examined. For this input case, a statistical analysis showed that the actual and equivalent systems were in close agreement and that an acceptable equivalence was obtained. The measure of comparison used was the F–test and the allowable error selected was 1%.

This research was conducted using mainly a dead-zone relay for the nonlinear element. However, this is only a start since any nonlinear analysis is applicable only for a specific nonlinearity. This research will be continued for the purpose of compiling an index of nonlinear elements and their corresponding Equivalent Gain Functions.

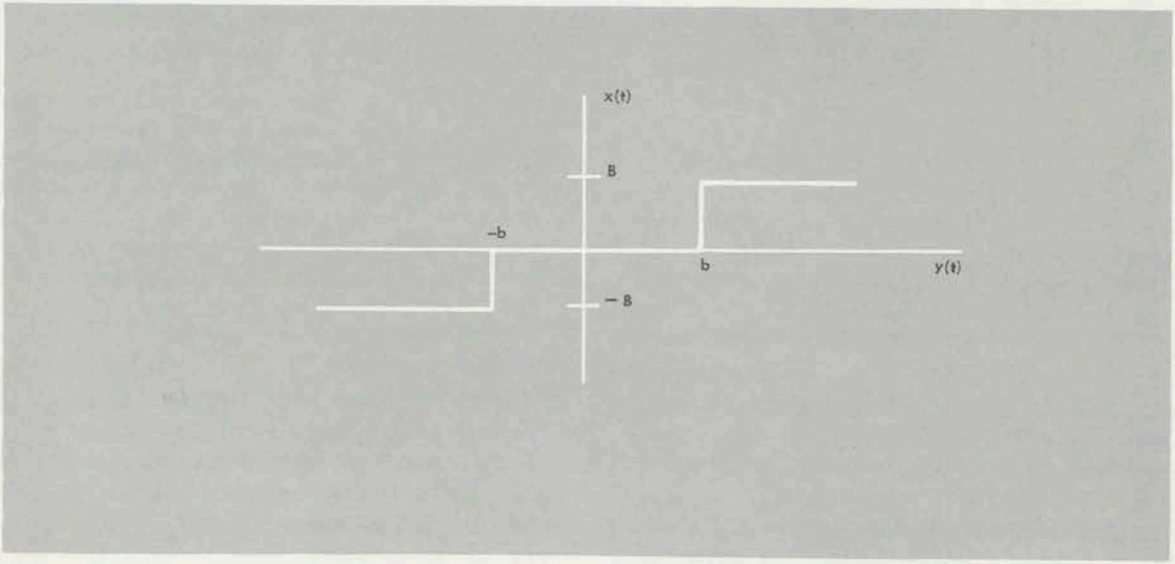


Fig. 8 Dead-zone relay characteristic.

humanities

H. E HAND
Head, Department of Humanities

During the last five years the faculty members in the Department of Humanities published numerous AFIT research reports and professional articles on the effective content, organization, and presentation of technical information to different kinds of audiences. In one research project, over 2,300 subjects have read and evaluated the effectiveness of various technical reports, and the experiment is continuing with different kinds of audiences varying in technical and verbal abilities. In the latest experiments, the influence of several variables on the effectiveness of a written technical communication (the description of a simple mechanism) was tested in a $3\times2\times2$ factorial experiment. The two audiences tested consisted of two groups of very bright men with known technical interests; however, only one group had received formal instruction in technical writing. One of the variables used in these experiments was the manner in which the size and shape of the mechanism were presented (drawings alone, drawings with written description, and written description alone). The effectiveness of the technical communication was measured by comprehension, reading time, the reader's impression of the author's knowledge of his subject matter and competence as a writer. Some of the important conclusions indicate that the manner in which the size and shape of the mechanism were presented did influence the comprehension, reading time, and judgment of author competence. Results from the experiment also suggested additional experimentation to test the hypothesis that an author's departure from a known or expected organization or format lowers the reader's impression of the author's knowledge of his subject. Interest in these experiments has been worldwide, and the results have gained general acceptance.

Results of Department research have also been published concerning those rhetorical elements that constitute effective technical writing. Studies of technical reports submitted by graduate students in introductory and advanced technical writing courses revealed that matters of style or mechanics seem to cause less trouble than content. An investigation of introductions in master's theses submitted by School of Engineering students yielded a similar conclusion: the technical writer often seems to have the most difficulty with the selection, arrangement, and proper emphasis of content.

Because the President's Science Advisory Committee has strongly urged that engineering students become proficient in information retrieval, studies have been conducted in which graduate students were asked to help in coding or indexing technical documents so that the information might be filed and retrieved by an automatic data processing system. The fact that a group of AFIT graduate students in the Reliability Engineering Program was successful in coding a large number of reliability documents suggests that such an exercise might be profitable for school libraries as well as for engineering students who are expected to help with the indexing, storing, and retrieving of technical information in their own fields.

Interest in the theory and practice of teaching methods and goals in all disciplines is reflected in a fifty-six page AFIT publication. The booklet describes an Engineering Instructors Course recently offered to faculty members in the School of Engineering. A number of articles have also been published concerning the relationship of courses in the humanities and social studies to the engineering curricula or, more specifically, to the education of engineers. Lecture notes on the history and philosophy of science have been compiled into a special booklet, *Twentieth Century Thought,* which is now being used in a course entitled "The Twentieth Century." Several studies have been published concerning the impact of our technological civilization on the writing, the interpretation, and even the teaching of twentieth century American novels. These findings are particularly useful in teaching courses in literature.

Engineering students, particularly those at the graduate level, find that a reading knowledge of German, French, or Russian is very helpful in their studies. Unfortunately there is not a great amount of available textbook material for the mature engineering student who is interested in reading foreign technical literature. Consequently, special course materials have been compiled by this Department that build on and extend the usual teaching materials used in beginning courses for foreign languages. Through the use of these materials and competent instruction, AFIT students, most of whom have a limited background in foreign languages, are able to become proficient readers of difficult technical literature in French, German, or Russian.

In addition to the research activities described above, there has also been some work with audio-visual aids, including closed-circuit television. Graduate students learning the techniques of orally communicating technical information have used closed-circuit television to tape and play back their own speeches and demonstrations.

Future research projects will continue to reflect not only the major areas of the Department's teaching responsibilities, but also the intensive specialization that even the humanist must possess.

Effective Technical Communications

R. M. DAVIS
Associate Professor of English

A series of experiments is being conducted to determine the most effective content, organization, and presentation for technical communications written in definable sets of circumstances. The experimental method being used is quite straightforward. A situation is assumed and a communication is written to meet its demands. Controlled variations are made in the communications so that several versions are produced for use in a factorial experiment. A criterion test is then developed for measuring the degree to which the purposes of the communication are attained. Each member of a homogeneous audience is assigned to read one of the versions of the communication, which are selected at random, and then all are given the same test. Statistical analyses of the test results are performed, and variations in performance on the test are assumed to be the results of differences in the interpretation of the different versions of the communication. To the degree that other situations are similar to the one assumed, communications organized and presented in the form found to be most effective in an experiment should better attain their purposes than those organized and presented in the other forms tested.

The subject of the message used in the three experiments thus far conducted is a simple mechanical device. The author is assumed to be experienced in technical writing and thoroughly familiar with the device. His task is to describe the structure and operation of the device to the reader. Nine audiences (something over 2,300 persons) have been tested. All subjects have been native speakers of English, and none has known anything about the author of the communication (the test passages are unsigned). The subjects knew nothing about the device until they read their passages because the device has not been produced commercially and nothing except the patent has been written about it. Distinctions between audiences were made on the basis of sex, age, intelligence, technical inclination, experience with written technical communications, and instruction received in technical writing.

The criterion test (20 questions of multiple choice) measured comprehension, reading time, the reader's impression of the author's competence as a writer and knowledge of the subject matter. Gross failure of a communication in any one of these areas might wholly offset its effectiveness in all other areas and nullify the effectiveness of the whole.

Because the experimental designs were factorial, it was possible to test the effects of several variables in each experiment. Variables tested have included introductory material, internal orienting material, headings, paragraphing, and the means by which the size and shape of the device and its parts are presented.

The results of the first three experiments have been very encouraging. From several hundred hypotheses tested, it has been found that it is possible to detect (1) differences in the effectiveness of the various versions of the message introduced by individual variables or by combinations of variables, (2) differences in effect in definably different audiences, and (3) differences between the four measurements taken of the effectiveness of the message. And, probably most important, the results appear to be repeatable. This experimental approach appears to provide a reliable predictive instrument by which the effect of a given item of content, form of organization, or manner of presentation may be determined in advance.

Following are some of the more interesting and more specific conclusions reached from reviewing the test results: (1) Comprehension was higher when drawings were included. However, contrary to what might be expected, the reader's comprehension was not increased when the drawing was accompanied by a verbal description of the machine and its parts; (2) the presence of drawings raised the reader's impression of the author's competence as a writer; (3) when sizes and shapes were presented by drawings alone, the material was read more quickly than when they were presented by drawings plus verbal description or by verbal description alone; (4) the introduction did not increase comprehension in any of the audiences tested; (5) the structural aids (introduction, internal orienting material, headings, and paragraphing) were of some benefit in some audiences, but not to the extent that might be expected; (6) overall comprehension increased between audiences to the degree that might be expected. Those individuals rated as being more intelligent understood the material better. Also, there is some indication that technical inclination raised comprehension above what might be expected at a given level of intelligence.

Considerable interest in this series of experiments has been shown by the academic and industrial communities and by the professional societies concerned with technical writing. Thus far, testing has been carried out at seven universities and three Air Force organizations, and the supply of subjects for testing has exceeded the demands of the experiments being conducted.

In another experiment, it was found that departures from a known or expected form or pattern lower the reader's impression of the author's knowledge of his subject matter. Two additional experiments to be run in the spring of 1967 are intended to shed further light upon this matter. In one, the variables will be parts of the expression itself (errors of agreement between subject and verb, misplaced modifiers, run-on sentences), and in the other, the variables will be concerned with copy preparation and reproduction (poor typing, ragged margins, smudged reproduction). It is expected that the results of these experiments will have significant implications for all manner of written communications mathematics

A. B. CARSON
Head, Department of Mathematics

Research in the Department of Mathematics during the past five years has been mainly in the areas of computer languages, functional analysis, operational calculus, point-set topology, reliability engineering, and mathematical statistics as outlined in detail in the following sections.

Computer Facilities

The computer facilities that are available to faculty and students for research include:

- *Digital*
  - An IBM 7044/7094 II Direct-Coupled System located at the Digital Computation Division, Aeronautical Systems Division, Wright-Patterson Air Force Base.
  - An IBM 1620 Data Processing System with 40K memory and card input/output located in the AFIT Digital Computer Laboratory.

- *Analog*
  - A 512-amplifier system dynamics simulator manufactured by Reeves Instrument Corporation and three 16–31R computers manufactured by Electronic Associates, Inc. This equipment is located at the Analog Computation Division, Aeronautical Systems Division.
  - Three TR–48 computers manufactured by Electronic Associates, Inc., and a DES–30 digital logic package, both located in the AFIT Analog Computation Laboratory.

Computer Languages

Computer language research in the Department has been directed toward the IBM digital computer in the following areas:

- FORTRAN compilers.
- Machine language assembly programs.
- FORTRAN library subroutine packages as aids in statistical simulation.
- Assembly language subroutines as simulation aids.

Two major programming systems were written: AFIT-improved FORTRAN and AFIT Symbolic Programming System (SPS). Both programs were improvements over the processors supplied by the manufacturer and they received wide distribution through the 1620 Users Group Library.

The AFIT FORTRAN compiler included the unformated input, built-in pre-compiler with a complete diagnostic list, provision for batch compiling without reloading, and provision for listing the assembly language compiled.

Features of the AFIT SPS assembly program included a significant decrease in assembly time, additions to the language, and provision for the assembly of relocatable programs.

Investigations in the computer languages for statistical simulations included studies of random-number generators and the designing and implementing of subroutines for existing programming systems. New Macro-ops were added to the assembly language and a package of related subroutines was added to the FORTRAN system.

Five AFIT M.S. theses have been written in the area of computer languages.

Functional Analysis

Techniques of geometric and nonlinear functional analysis are applied to problems of best approximation. Banach spaces of special geometrical type, such as (UR) or (DL), are characterized by approximation properties. Methods for obtaining algorithms convergent to best approximations are studied. Approximation out of convex sets is analyzed via "smoothness" properties of the metric projection. A theory of differentiable best approximation is developed and applied to obtain results on the linear and lipschitzian behavior of best approximation in general Banach spaces and in L^p-spaces. This theory also makes possible several examples and counter-examples in approximation theory, such as the existence of

Chebyshev subspaces supporting discontinuous metric projections. Further research exploits the Banach manifold structure of the projection kernel and is aimed at providing intrinsic characterizations of smoothness properties of the metric projection supported by a Chebyshev subspace.

Problems of approximation in function spaces were studied. A relation between the existence of best approximators (and also of largest and smallest best approximations) and interposition properties of the approximator set was established. Many applications of a theory along this line of development are possible; for example, approximation by continuous functions on a paracompact space, lower semi-continuous functions on a topological space, subharmonic functions on a region in the plane, distance-decreasing functions on a metric space, and linear or convex functionals on a bounded subset of a Banach space.

In linear analysis, a new formula for the spectral radius of an operator was devised and applied to establish a decomposition theorem for operators whose spectrum fails to intersect the unit circle—such a theorem being suggested by a problem in differential equations.

Operational Calculus

Mikusinski has developed an operational calculus which provides a rigorous basis for delta "functions" and is applicable to the solution of certain boundary-value problems. Mikusinski gives a sequential definition of the convergence of his "operators"; however, this definition is not adequate for defining a topology on the field of operators.

The problem of convergence of operations was studied and a topology was defined on a sub-algebra of the field of operators. With this topology, Mikusinski's theory is given a firm foundation, and all concepts, such as differentiation or continuity of operator-valued functions of a real variable, are merely extensions of the usual definitions.

Point-Set Topology

The following topics are currently being studied in point-set topology: knot theory, subsets of n-books in Euclidean three-space (E^3), manifolds, dendrites, dendroids, tapered neighborhoods, cellularity, and arcs. These studies have led to a characterization of tame 2-spheres in E^3, necessary and sufficient conditions that certain discs in E^3 be tame, and a sufficient condition that knots in E^3 be prime. Ultimate goals include a partial solution to the knot classification problem and a classification of arcs in E^3.

Reliability Engineering

The problem of obtaining system reliability confidence limits from component test data is an important one in reliability engineering, and many authors have considered various approximate and exact methods of solving this problem. Because of the flexibility of the Monte Carlo method, research at AFIT has concentrated on using this method. Programs have been written for the IBM–7094A computer which enables one to obtain system confidence limits for a wide range of component failure models. A program to specify component test and demonstration requirements has also been written for the IBM–7094A computer. This program, based on specified system reliability confidence limits, uses the exponential distribution for the underlying failure model. Three AFIT M.S. theses have been written on problems in system reliability.

Several simulation studies of Air Force systems have been undertaken by students in the Graduate Reliability Engineering program. The most notable include:

- A study of the effectiveness, measured in terms of missiles fired and circular error probability, of the B–52 Skybolt weapon system.
- The development of a procedure for setting the time between overhauls on helicopter gear-box assemblies.

• A simulation of the machine translation system used by the Foreign Technology Division, Wright-Patterson Air Force Base, to translate Russian documents.

Each of these studies has led to a simulation model which can be used for making the best decisions in the management of a particular system under consideration.

Mathematical Statistics

Research in mathematical statistics has been mainly on the estimation of parameters of statistical distributions. Estimators and their properties have widespread application wherever the mathematical models studied have been applied, such as in reliability engineering. The results developed are applicable to life testing, metal fatigue and fracture problems, corrosion pitting, gust loads on aircraft, breakdown voltages in transformers, analysis of life test data, bioassay analysis, psychometrics, cancer research, sanitary engineering, and soil conservation. Both point and interval estimation of the parameters are considered and are based on complete, singly- or doubly-censored samples. In addition, estimators are constructed, based on selected order statistics. Methods of estimation considered included simultaneous and conditional best linear unbiased or maximum-likelihood estimation. Maximum-likelihood equations were constructed for complete and censored samples from the normal, log-normal, gamma, Weibull, logistic, and extreme-value distributions. Programs for computing the maximum-likelihood estimates were devised and the elements of the asymptotic variance-covariance matrices were computed. Using Monte Carlo techniques, the closeness of the estimator properties to the asymptotic values has been investigated as a function of sample size n. Simultaneous maximum-variance, unbiased, linear estimators for the scale and location parameters of the Weibull and Gamma densities were computed by using selected order statistics from the complete and censored samples. Similar estimators were also obtained for the logistic and the extreme-value distributions. This research has been performed jointly with the Aerospace Research Laboratories, Wright-Patterson Air Force Base, and so far thirteen AFIT M.S. theses have been written on mathematical statistics.

Optimal Control Theory

An optimal control system can be defined in terms of (1) a differential equation which describes the behavior of the system, (2) a set of admissible controls, (3) a target set, (4) a constraint set for the trajectories of the differential equation, and (5) a cost functional associated with each trajectory. In an optimal control problem, an admissible control is chosen which defines a trajectory of the differential equation, together with the constraint set, so that the trajectory reaches the target set with the minimum value of cost functional. A wide variety of such control problems have been solved by using Pontryagin's Maximum Principle. The calculus of variations and dynamic programming have also been applied but with less success. All these techniques could be described as variational approaches.

Simultaneous with the development of these techniques, optimal control problems were investigated with the aid of functional analytic tools. In the past year, an investigation was initiated at AFIT which combines functional analysis with nonlinear programming. With this approach, many problems can be solved more readily. The following problem illustrates this approach.

Assume that a physical system can be described by the differential equation

$$x' = Ax + Bu$$

where A and B are matrices of bounded measurable functions of orders $n \times n$ and $n \times u$, respectively, and u is an $r \times 1$ vector of elements in some L_p space. Given an initial condition x_0, the variation of parameter formula gives

$$x(t)=X(t)\ [x_0+\int_0^t x^{-1}(s)B(s)u(s)\,ds]$$

as the solution to $x' = Ax + Bu$. Suppose it is desired to drive the solution to the origin in some time T. Furthermore, suppose the components of u are to satisfy $|u_i(t)| \leq 1$ and finally the cost functional is

$J(u) = ||u_1||^2 + \ldots + ||u_r||^2$ where $||u_i||$ is the L_2 [0, T] norm. This is equivalent to asking for an admissible u such that $x_0 = -\int_0^T x^{-1}(s)B(s)u(s)\,ds$ and $J(u)$ is minimized. Let K denote the set of all r-tuples of $L_2[0, T]$ functions which satisfy

$$x_0 = -\int_0^T x^{-1}(s)B(s)u(s)\,ds.$$

Let

$$G(u) = \begin{bmatrix} u_1^2(t) - 1 \\ \vdots \\ u_r^2(t) - 1 \end{bmatrix}$$

then the problem described can be formulated as follows. Choose $u \epsilon K$ such that

$G(u) \leq 0$ (i.e., $u_i^2(t) - 1 \leq 0$, $i = 1, 2, \ldots r$)

and such that J is minimized. This is a typical nonlinear programming problem. It has been shown that a theorem of Hurwicz concerning Lagrangian saddle points in locally convex spaces can be considerably strengthened if the setting is a Banach space. Application of this result to the problem specified above yields the well-known saturation optimal control. This theorem has been applied successfully to many linear problems in which the cost functional J and constraint function G are Frechet differentiable. Current research in the Department is being directed toward generalization of the nonlinear programming approach so that nonlinear problems and cost functionals which have only a directional derivative can be handled. For example, the problem described above can be treated when the elements of u belong to L_1 [0, T] and $J(u) = ||u_1|| + \ldots + ||u_r||$ where $||u_i||$ is the L_1 [0, T] norm. In this case, although J has only a directional derivative, the usual dead-zone control can be easily obtained.

mechanical engineering

A. J. SHINE
Head, Department of Mechanical Engineering

Most of the research studies in the Department of Mechanical Engineering have been in direct support of or related to research efforts of various laboratories at Wright-Patterson Air Force Base. These studies have been conducted primarily in heat transfer, propulsion, and gas dynamics.

The Department laboratories consist of a rocket test facility for conducting tests on engines in the 100-pound thrust size; apparatus and instrumentation for studying detonation waves propagating in flowing gases; two low-speed wind tunnels, one horizontal and one vertical, used almost exclusively for two-phase flow studies; four interferometers; a 4″ × 8″ cross-section shock tube; several compressible flow stands supplied with up to 1.2 lb/sec of dry, oil-free air at 100 psi; vibration equipment for heat transfer studies; and several schlieren optical systems.

The most extensive studies were conducted to investigate the effect of vibrations on the heat transfer rate, the fluid flow and heat transfer in the entrance region between two plates, the cooling of small rocket motors by reverse flow of one of the propellants, the flow through a moving orifice, the flow and heat transfer characteristics of a two-phase (air-water) mixture, and the propagation of a detonation wave into a flowing combustible gas. The most recent studies pertain to two-phase flow, detonation propagation, and the effect of electric fields and vibrations on heat transfer.

The results of some of the studies are now presented.

Reverse-Flow Cooling

The method for achieving cooling by reverse flow is to obtain a film of one of the propellants (hydrogen) on the inner wall of the combustion chamber by injecting it forward from the rear of the engine (immediately upstream from the throat of the nozzle). The basic engine used had a spherical combustion chamber 4 inches in diameter and a nozzle throat 1.0 inch in

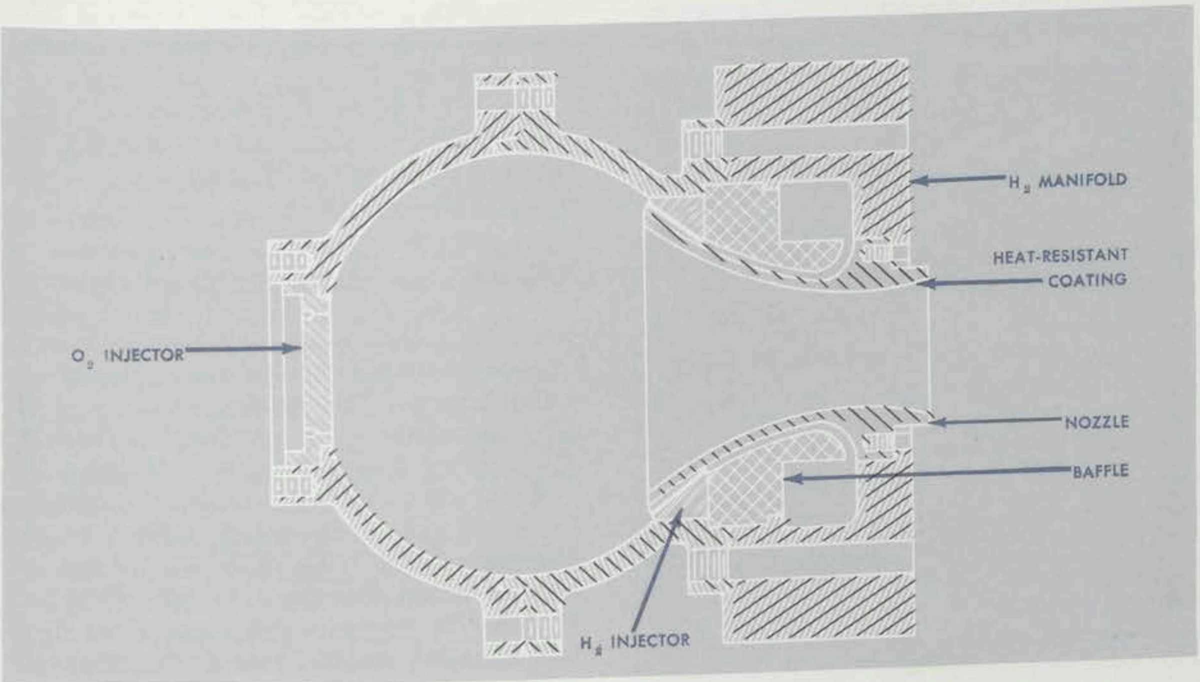


Fig. 1 Basic engine configuration.

diameter (a cross-section of the engine is shown in Fig. 1). The spherical chamber consisted of two hemispheres so that the combustion chamber length could be increased by inserting cylindrical sections between the hemispheres. The interferometer studies verified the attachment of the film in the chamber, even when the chamber length was doubled in this manner.

The first operation of the engine showed that the cooling method was very effective but thrust performance was poor. Most of the subsequent effort was directed to increasing the thrust by improving the oxygen and hydrogen injection and varying the chamber length. In this work the chamber pressure was varied from 60 to 150 psia and the mixture ratio from 1 to 9. The results indicated that a spherical engine is the best configuration with combustion efficiencies as high as 97 per cent.

Effect of Vibrations on Heat Transfer

A series of studies have been conducted to learn about the effect of transverse vibrations on the heat transfer from cylinders to air which is stationary. The effect was determined by measuring the change in heat flux at constant cylinder temperature and by schlieren and interferometer optical observations while varying vibration intensity of the cylinder.

The cylinders varied in diameter from 0.032 to 0.75 inches, and the cylinder-to-ambient-air temperature varied from 50° — 200°F. The intensity of vibration, defined as the product of frequency and amplitude, included frequencies up to 90 cps and amplitudes up to 0.75 inches. The results of these studies show that for vibration intensities below a rather definite critical value, the heat transfer rate is essentially unaffected and is that of a stationary cylinder. This lack of influence is also borne out by observation of the boundary layer with the optical systems. Beyond this threshold intensity the heat transfer rate increases rapidly with vibration intensity until the rate coincides with that predicted by the generally accepted curve for forced-convection (McAdams) where the velocity for the vibrating system is taken to be the average velocity of vibration. Further increases in intensity cause increases in heat transfer rate that agree quite well with those of the forced-convection curve. Again the optical observations substantiate the heat flux measurements by showing disturbances in the boundary layer which increase in intensity as the vibration intensity is increased beyond the threshold level. The disturbances appear to be eddies which become more numerous and smaller as the vibration intensity increases. The effects of cylinder diameter and temperature, to the extent that these have been varied to date, appear to be adequately absorbed when the results are presented in terms of Nusselt, Grashof, Prandtl, and Reynolds numbers. However, the Reynolds number, based on the average velocity or intensity of vibration, does not adequately indicate the beginning of the transition in the nature of the flow in the boundary layer which causes the change in the heat-transfer rate. It was observed that increases in frequency of vibration delayed the transition. Figure 2 is a typical presentation of the heat-transfer results, and Fig. 3 is a typical schlieren photographic presentation of the boundary layer at low- and high-vibration intensity.

Flow Through Moving Orifices

Experimental studies have been conducted to learn about the effect of the motion of an orifice transverse to the direction of flow of a stream of air on the rate of flow through the orifice.

A disc that could be rotated at speeds up to 14,000 rpm was mounted inside a 4-inch diameter tube for some of the studies and inside an 8-inch diameter tube for additional studies. The pressure drop across the disc was recorded, and the rate of flow through the disc was measured by an orifice upstream of the entrance to the tube. Tests were con-

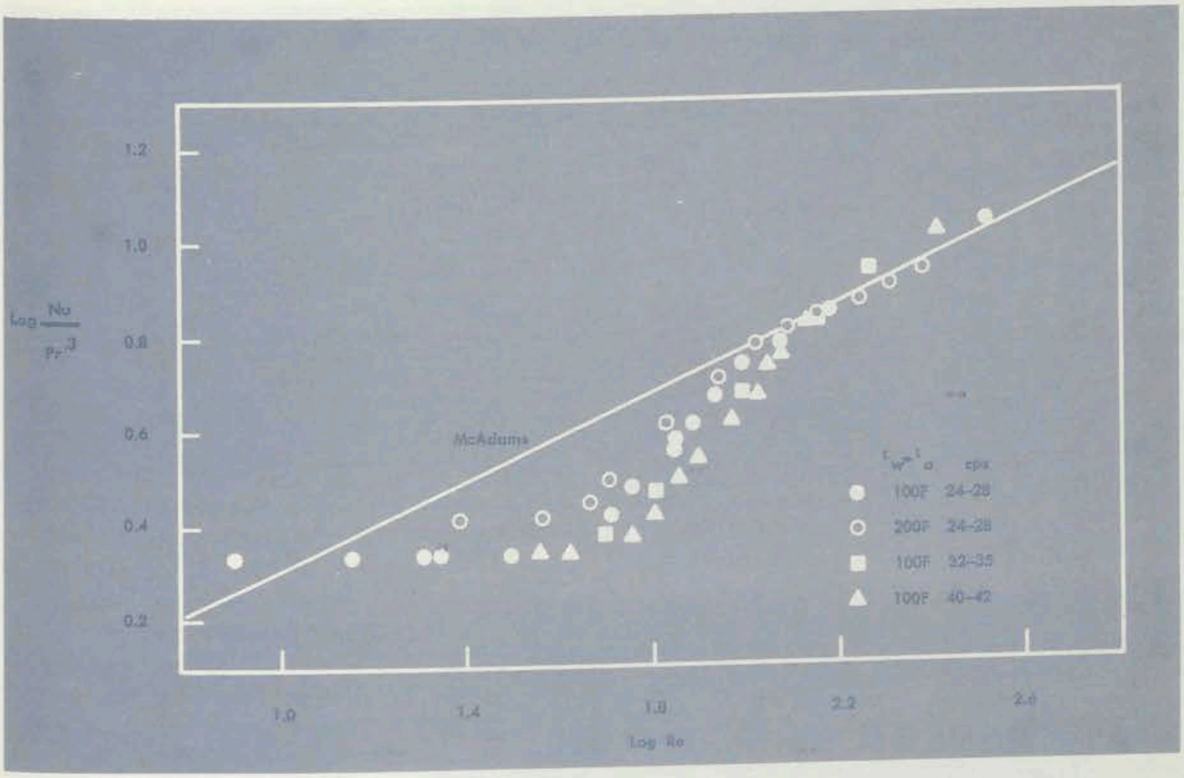


Fig. 2 Variation of the heat transfer coefficient with vibration intensity for the 0.12-in. diameter test cylinder.

ducted with about twenty discs to vary the number of orifices per disc as well as the size and radial location of the orifices.

The results indicate that as the disc speed is increased, the rate of flow remains essentially constant until a certain minimum speed is attained beyond which the rate of flow decreases rather rapidly with speed. For a given tube diameter, the results of all the tests were conveniently presented in terms of two nondimensional parameters involving the rate of flow $\dot{m}$, orifice area A, upstream air density ρ, orifice pressure drop ΔP, radial location of orifice R, and the disc speed ω. Figure 4 is a typical presentation of the results. The low-speed portion of the performance curve can be altered by slight changes in the orifice geometry from a constant diameter bore to give an immediate increase or decrease in the flow rate as the disc speed is increased.

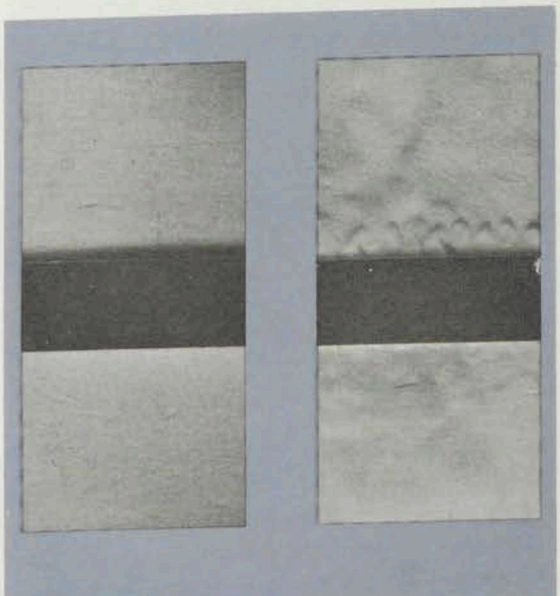


Fig. 3 Schlieren photographs of boundary layer at low- and high-vibration intensity.

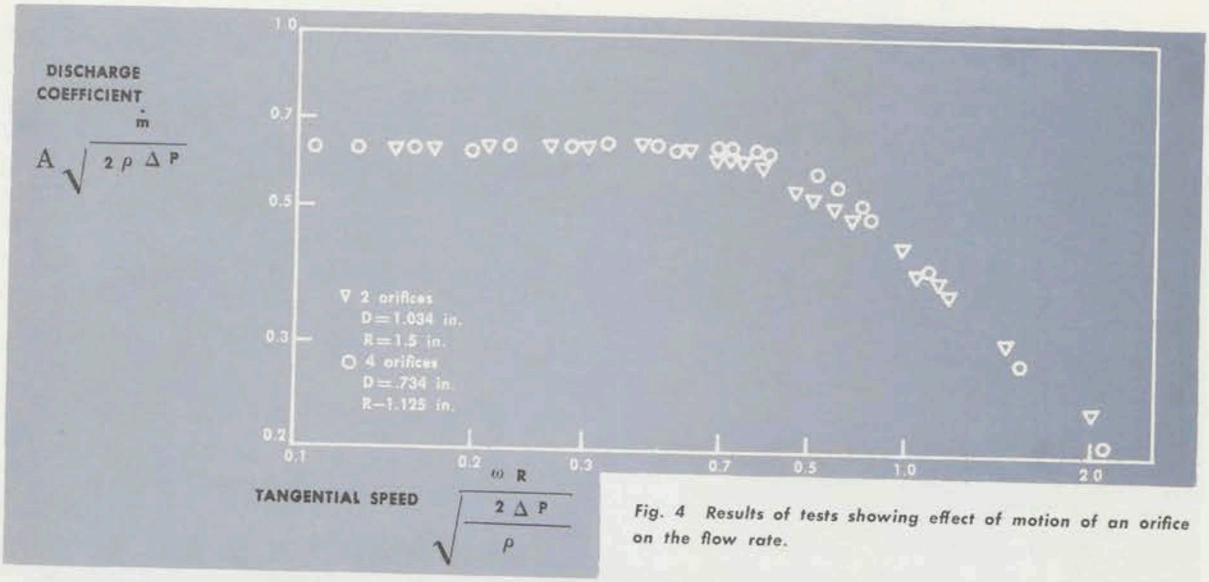


Fig. 4 Results of tests showing effect of motion of an orifice on the flow rate.

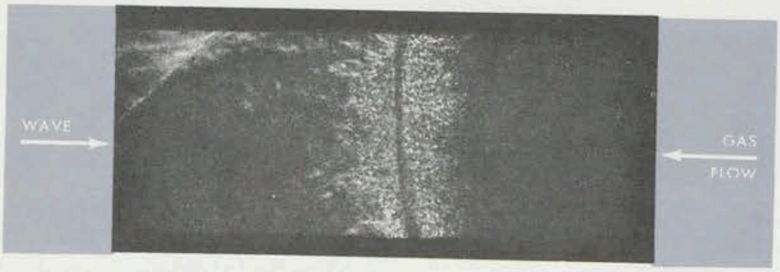


Fig. 5 Schlieren photograph of a detonation wave propagating into a Mach 4 hydrogen-oxygen gas mixture.

Behavior of a Detonation Wave in a Flowing Combustible Gas

Apparatus was designed and constructed to measure the relative wave velocity and to photograph the wave profile as a fully developed detonation wave propagated against a flow of a stochiometric mixture of hydrogen and oxygen gas. The Mach number of the mixture was varied from 0.14 to 4.

The detonation wave was generated by the combustion of a hydrogen-oxygen mixture in an initiator tube 1.5 inches in diameter by 84 inches in length and closed by a mylar diaphragm. This wave entered the flowing gas in the 1.5-inch diameter detonation tube. The length of the detonation tube, which was in three sections, varied from 2 to 7 feet. A specially constructed section, having 1″ × 5″ windows, was inserted to obtain schlieren photographs of the wave.

The subsonic-flow results indicated that the absolute detonation-wave velocity relative to the gas was independent of the speed of the flowing gas. But the supersonic-flow results indicated the presence of a strong wave which affected the pressure profile in the tube. At the highest flow velocity, Mach 4, the experimental wave-velocity was about 25 per cent above that predicted. The schlieren photographs of the wave indicated propagation into the boundary layer and showed a convex curvature of the complete wave front in the Mach 4 flow. A typical schlieren photograph of the wave at a Mach 4 gas flow is shown in Fig. 5.

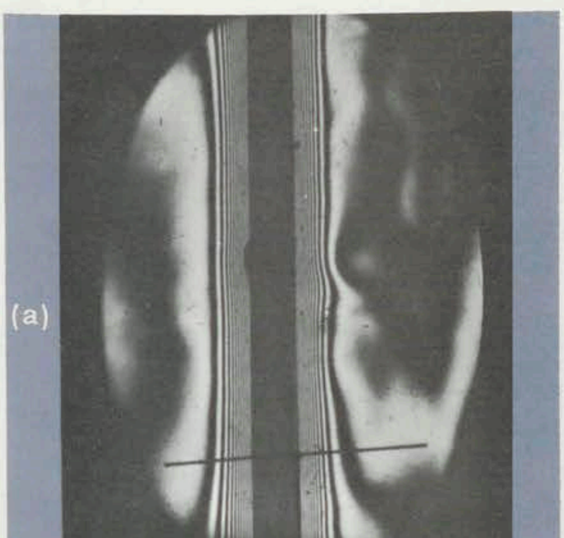
Effect of Electrostatic Fields on Convective Heat Transfer

M. E. FRANKE
Associate Professor of Mechanical Engineering

Methods of increasing the rate of heat transfer are of continuing interest. Recently, several studies [1-4] have been conducted to determine the influence of electrostatic fields on free-convection heat transfer in gases. These studies showed that the rate of heat transfer from a vertical plate could be significantly increased by wire-to-plate gaseous discharge.

The influence of vortices in boundary-layer flows is also of current interest. [5] In flows over two-dimensional backward-facing steps, striations that were parallel to the flow were found on plates in the reattachment region. [6] The striations were apparently caused by counter-rotating streamline vortices in the boundary layer. Significant increases in the local rates of heat transfer were observed. Analytical studies concerning stagnation-point flows have shown that vorticity, present in the oncoming flow with an intensity which is small but still larger than some neutral intensity, can reach the boundary layer with greatly magnified intensity and cause significant increases in the wall heat-transfer rate. [7] In other studies, increases in heat transfer were found in the free-convection flow on an inclined plate about the same time that longitudinal convection rolls were observed. [8] Increases in heat transfer have also been observed when vortex rolls appeared in fully developed flows between two horizontal flat-plates. [9]

In an attempt to take advantage of the influence of vortices and the effects of electrical discharge in gases, a research program



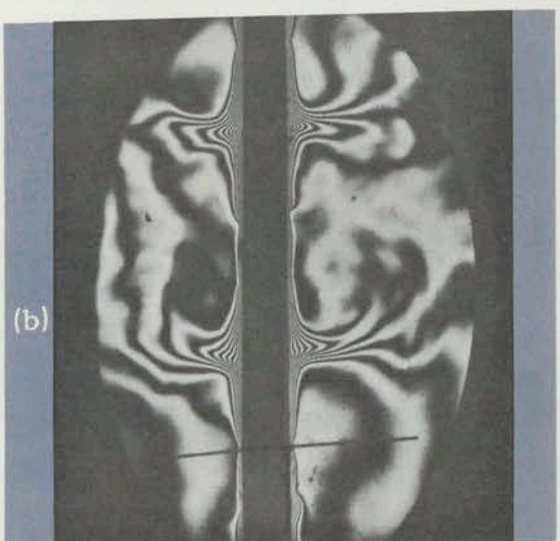


Fig. 6 Vertical interference photographs of the thermal boundary layer on a heated vertical phenolic plate in air. Fig. 6(a) is for a plate without an electric field; Fig. 6(b) is for a field of 6.9 KV and 90 μA. Corona wires were placed vertically on the plate, 6 positive and 4 negative wires on each side. The plate-to-ambient temperature difference was approx. 65°F.

was initiated. It was found that columnar, counter-rotating vortices could be produced in the free-convection boundary layer on a heated vertical flat-plate using a high-voltage d.c. electric field. The vortex motion of the air resulted from the electric wind that was established between several small diameter wires having alternate high-voltage and ground potential and placed vertically on the surface of a phenolic plate. The thermal boundary layer was influenced considerably by the electric field (see Figs. 6a and b). The rate of convective heat transfer from the plate for the conditions given in Fig. 6 was more than twice as much as that without an applied electric field.

REFERENCES

[1]Velkoff, H.R., "Electrofluidmechanics: Investigation of the Effects of Electrostatic Fields on Heat Transfer and Boundary Layers," ASD TDR-62-650, Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, 1962.

[2]Marco, S.M., and Velkoff, H.R., "Effect of Electrostatic Fields on Free-Convection Heat Transfer from Flat—Plates," ASME Paper 63-HT-9, 1963.

[3]O'Brien, R.J., "The Effect of an Electric Field on Heat Transfer from a Vertical Plate in Various Gases over a Range of Pressures," M.S. Thesis, GA/ME/64-3, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 1966.

[4]Robbins, G.W., "The Effect of an Electric Field on Heat Transfer from a Vertical Plate in Nitrogen, Helium, and Freon 12," M.S. Thesis, GA/ME/66A-7, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 1966.

[5]Scherberg, M.G., Private Communication, Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1965.

[6]Ginoux, J.J., "Experimental Evidence of Three-Dimensional Perturbations in the Reattachment of a Two-Dimensional Boundary Layer at Mach 2.05," TN-1, Training Center for Experimental Aerodynamics, Belgium, (to be published in 1968).

[7]Sutera, S.P., "Vorticity Amplification in the Stagnation-Point Flow and its Effect on Heat Transfer," **Journal of Fluid Mechanics**, 21, 513-534 (1965); also Aerospace Research Laboratories Report, ARL 64-91, Wright-Patterson Air Force Base, Ohio, 1964.

[8]Persen, Leif N., "A Simplified Approach to the Influence of Gortler-Type Vortices on the Heat Transfer from a Wall," Aero-Space Research Laboratories Report, ARL 65-88, Wright-Patterson Air Force Base, Ohio, 1965.

[9]DeGraff, J.G.A., and van der Held, E.F.M., "The Relation Between the Heat Transfer and the Convection Phenomena in Enclosed Plane Air Layers," **Applied Science Research**, A3, 393-409 (1953).

Laminar Forced-Convection in the Entrance Region Between Parallel Flat-Plates

J. E. HITCHCOCK

Associate Professor of Mechanical Engineering

Theoretical and experimental studies of laminar forced-convection in the entrance region between parallel flat-plates have been conducted in the Department of Mechanical Engineering during the past three years.

The entrance region is a formidable problem compared with the extensively investigated, fully developed flow and heat-transfer region of channels. Entering fluid velocity and temperature are assumed to be uniform across the channel, and one must deal with simultaneously developing momentum and thermal boundary layers. The motivation for this effort is apparent when one considers that in channels with a uniform surface temperature, a fluid is heated or cooled by approximately 50 per cent before fully developed heat transfer is established. Even in channels with a uniform surface heat flux, a reduction in required heat transfer area can be obtained by using the higher convective heat transfer coefficients in the entrance region.

The following assumptions were employed in the theoretical analysis of the entrance region: the flow is laminar, steady, and two-dimensional; all fluid properties are constant; buoyant forces are negligible compared with viscous and pressure forces; viscous dissipation and work of compression are negligible compared with heat conduction; the usual boundary-layer assumptions apply; and the fluid velocity and temperature are uniform across the entrance. Two thermal conditions were considered: (a) two parallel plates at the same uniform temperature and (b) one plate at a uniform temperature, the other with zero heat transfer (insulated). The equations of motion and of conservation of mass and energy, consistent with the foregoing assumptions, were written in finite difference form and solved numerically with the aid of an IBM 7094 digital computer. The most important results of these numerical calculations and those previously published by other investigators are summarized by the following empirical equations for the mean Nusselt number Nu_M based on the plate spacing s and the log mean temperature difference between the plates and the fluid:

For heat transfer at both plates

$$Nu_M=3.77+\frac{0.066(Re_d\ Pr\ s/2x)^{1.2}}{1+0.10(Pr)^{0.87}(Re_d\ s/2x)^{0.7}}$$

For heat transfer at one plate

$$Nu_M=2.43+\frac{0.16(Re_d\ Pr\ s/2x)^{1.2}}{1+0.24(Pr)^{0.87}(Re_d\ s/2x)^{0.7}}$$

where Re_d is the Reynolds number based on equivalent diameter, Pr is the Prandtl number $(0.1 \leqq Pr \leqq 10.0)$, and x is the distance from the channel entrance.

In the experimental investigation, laminar forced-convection in a parallel plate device was examined with a Mach-Zehnder interferometer. A schematic diagram of the device is shown in Fig. 7. The principal parts consisted of two flat, parallel copper plates which, with integral hot-water jackets, provided the isothermal boundary conditions. The plates, 1/2 inch apart, were aligned and supported by plexiglass cylinders. Air entered the upstream cylinder from 1/16 inch diameter holes drilled along the length of the inner plexiglass tube, emerged from the inner tube in the opposite direction from the channel entrance, and then passed through a fine-mesh screen to ensure a uniformly distributed, quiescent flow. In addition, wood inserts provided a converging section which prevented gross disturbances near the entrance at high flow rates. Clean, dry air at very near atmospheric pressure was used in all tests. The 60° – 70°F. temperature difference between the plates and the air, together with the mercury-vapor light source and 12-inch-wide test section, produced 13 to 17 fringes (isotherms) on infinite-fringe interferograms. Six interferograms, representing the highest and lowest

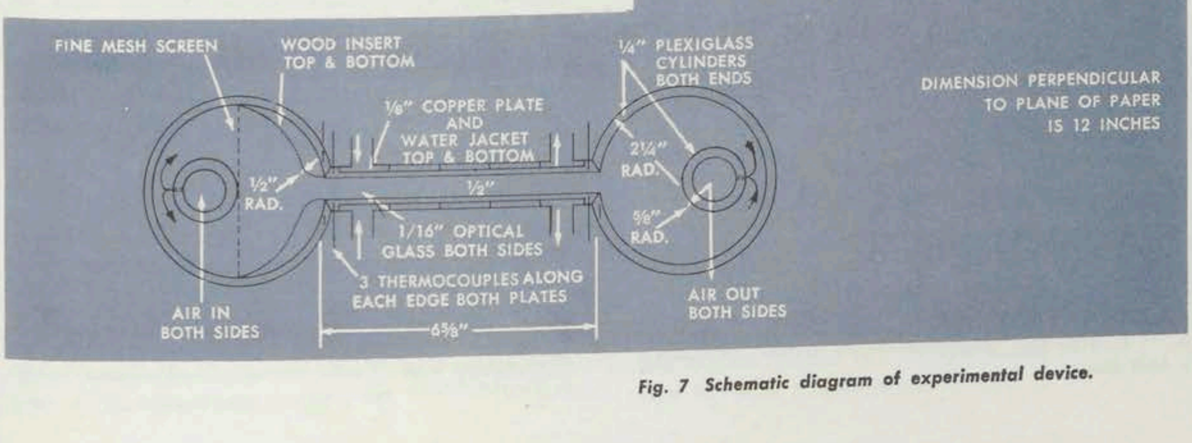


Fig. 7 Schematic diagram of experimental device.

Reynolds number used for each of three thermal boundary conditions, are shown in Fig. 8. The first reference wire (on the right) was located 1 inch from the entrance; the second, 4 inches. Typical dimensionless temperature-defect profiles are shown in Fig. 9. Each circle specifies the nondimensional temperature and position where a fringe intersects a reference wire. The lines

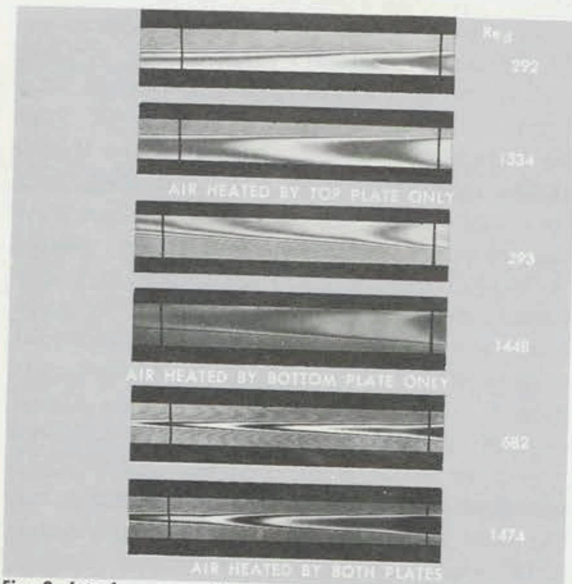


Fig. 8 Interferograms. Flow is from right to left.

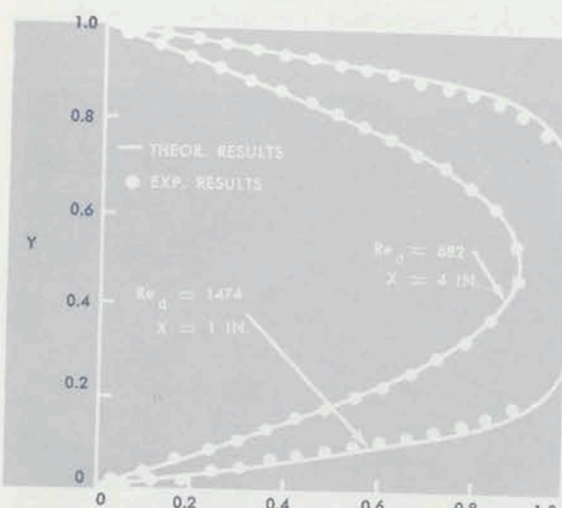


Fig. 9 Dimensionless temperature-defect profiles (air heated by both plates).

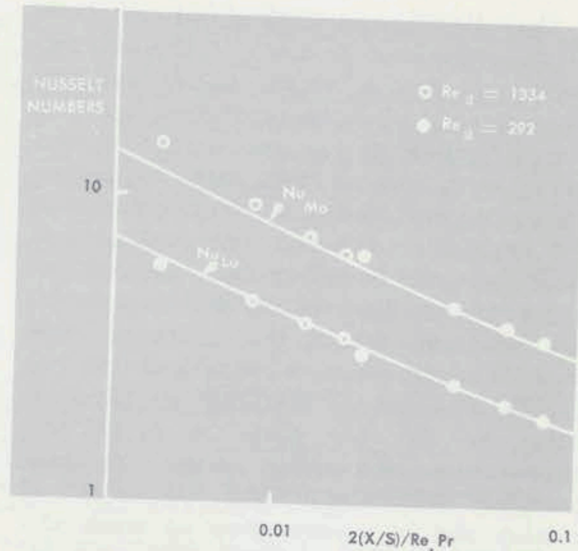


Fig. 10 Nusselt numbers (air heated by top plate only). For each set of four similar points, x = 1, 2, 3, and 4 in., from left to right.

were constructed with data from the theoretical calculations. The agreement is excellent for the data taken 4 inches from the channel entrance.

Local and mean Nusselt numbers, based on plate/fluid temperature difference, are shown in Fig. 10 for the test in which air was heated by the top plate only. Again, the lines are theoretical results. In general, local Nusselt numbers are within 5 per cent, and mean Nusselt numbers are within 10 per cent of the theoretical values for $x > 2$ inches, or 4 times the channel spacing. The differences existing closer to the entrance are due to finite initial momentum and thermal boundary-layer thicknesses. As a result of this detailed experimental examination of an entrance region, considerable confidence has been gained in the assumptions and methods employed in theoretical analyses of this kind of problem.

Results of this research were reported in a paper presented at the 1966 Winter Annual Meeting of the American Society of Mechanical Engineers, Paper No. 66-WA/HT-16, "Laminar Forced-Convection in the Entrance Region Between Parallel Flat-Plates," by W. E. Mercer, W. M. Pearce, and J. E. Hitchcock.

Boundary-Layer Investigation in Two-Phase (Gas-Liquid Spray) Flow

H. E. WRIGHT
Associate Professor of Mechanical Engineering

Preliminary probings of two-phase flows across cylindrical bodies show anticipated relatively high heat-transfer characteristics which have led to an extended interest in the general phenomena involved. Some of the parameters that are now known to have an influence on the heat transfer and attendant flow characteristics are the liquid gas content ratio of the spray, distribution of droplet size, droplet momentum, relative velocity between the droplet and air stream, and conventional gas flow Reynolds number. Other parameters that may be expected to influence the characteristics of interest are body shape, wetting property of the liquid used, surface condition of the body, temperature increment between body and oncoming flow, presence of surface vibrations, presence of large chain polymers in the fluid, and surface temperature distribution.

The objective of this research project is to perform analytical and experimental investigations of the boundary layers that are developed on a constant-temperature surface when subjected to a two-phase (gas-liquid spray) flow field. This requires the study of the hydrodynamic and thermodynamic boundary layers and the flow field outside the boundary layer. The technical guidance for this program has been provided by the Thermomechanical Branch of the Aerospace Research Laboratories.

Two low-speed wind tunnels are available for this research. Both are capable of handling two-phase flow systems. The first tunnel is a vertical down-draft open wind tunnel with a maximum test-section gas velocity of 160 ft/sec. The test section is made of plexiglass with a 10″ × 10″ cross section. The second tunnel is a horizontal

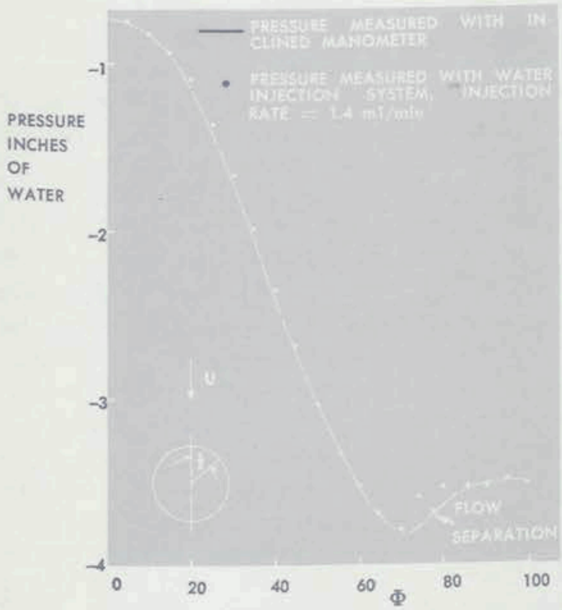


Fig. 11 Pressure on cylinder vs. Φ for 1.5-inch diameter cylinder. Air Reynolds number = 5.64 x 10⁴.

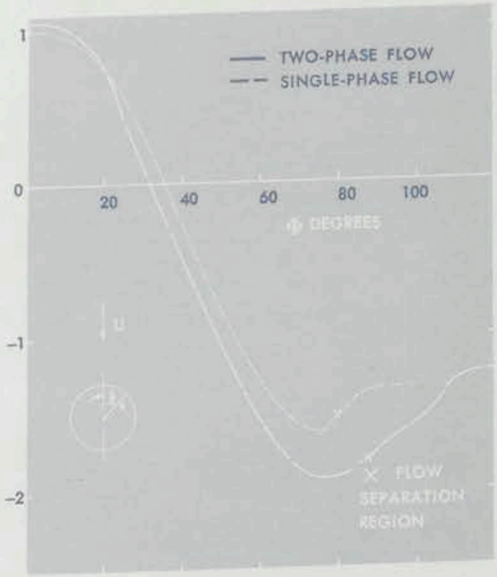


Fig. 12 Pressure coefficient vs. Φ for two-phase flow over 1.5 inch diameter cylinder. Gas Reynolds number = 5.64 x 10⁴; mass flow ratio of water to air = 0.045.

tunnel with the same flow characteristics as the first, but with a 14″ × 30″ test section.

The research program has been divided into three distinct areas to date.

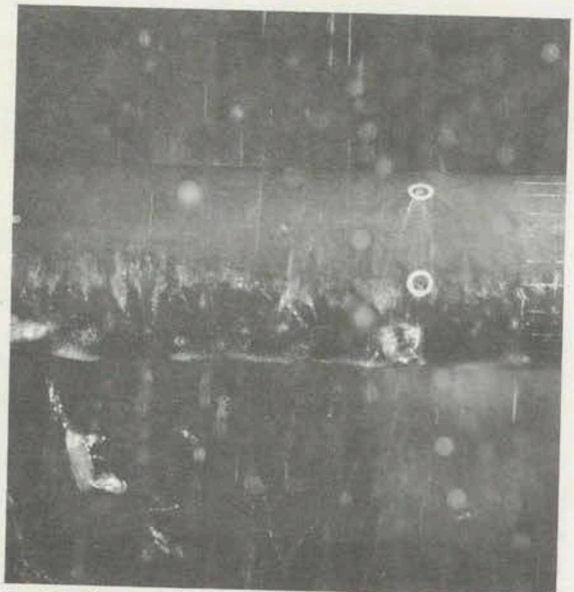


Fig. 13 Photograph of flow separation. Gas Reynolds number = 5.64 x 10^4; mass flow ratio of water to air = 0.045.

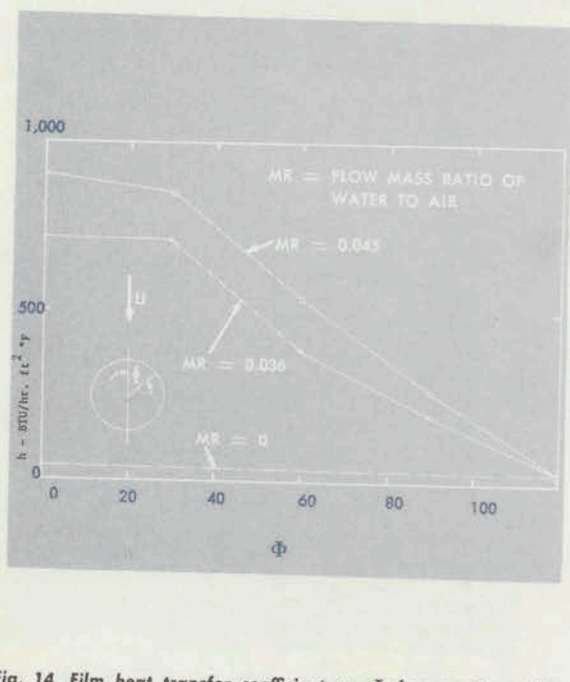


Fig. 14 Film heat transfer coefficient vs. Φ for gas Reynolds number 4.8 x 10^4 (1.5-inch diameter cylinder).

1. The development of research techniques for the investigation of two-phase flow was the basic problem for a doctoral dissertation. The dissertation had as its major objective the investigation of the hydrodynamic boundary layer in the region where the flow separated from a curved surface. A technique for the measurement of the pressure distribution over a surface when subjected to two-phase flow was developed. The system was composed of a conventional strain-gauge pressure transducer and liquid-filled pressure lines. The lines were pressurized in order to bleed a small amount of liquid into the liquid film while the pressure was being recorded. Typical results of these measurements are displayed in Fig. 11 for single-phase (gas) flow, and Fig. 12 for two-phase (gas-liquid spray) flow. The separated liquid film from a circular cylinder was made visible by the addition of a small amount of wetting-agent to the liquid film. The wetting-agent was injected through a pressure tap into the liquid film in the region of the forward stagnation point. Figure 13 is a typical photograph of the separated flow.

2. The second area of investigation was the determination of the local and average heat-transfer coefficient for a heated circular cylinder with transverse two-phase flow. This was the subject of two independent studies for M.S. degrees. The first study was limited to the conversion of the horizontal wind tunnel to receive two-phase flow and to the fabrication of a test cylinder (1.5 inches in diameter, 10 inches in length) which would provide local heat-transfer data. The second study completed the investigation. Figure 14 presents a typical curve of the local heat-transfer coefficient vs. angle measured from forward stagnation point.

3. The third area of research, which is the current effort, considers two problems: first, the study of the heat-transfer characteristics of an elliptical cylinder exposed to two-phase flow, and second, an investigation of the flow field in the region of the forward stagnation point. The second problem is the subject of two theses.

mechanics

D. W. BREUER
Head, Department of Mechanics

Research in the Department of Mechanics over the past five years has spanned the areas of dynamics, structures, metallurgy, and materials, and has included studies in biomechanics and space sciences.

Biomechanics

Several thesis studies have been conducted on the dynamics of the human body. These have been sponsored by the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, and have included investigations of man's ability to maneuver and perform tasks under reduced gravity. One sequence of studies concerned man's walking ability at various g-levels. A specially designed ramp for measuring foot reactions was used in a zero-g aircraft for tests on human subjects to determine the lower-g limits for walking. Data were obtained for subjects wearing both space suits and ordinary clothing. Man's dynamic characteristics and his ability to stabilize and control his behavior under zero-g conditions have also been investigated. These particular studies have resulted in the development of a mathematical model of man's inertial characteristics. To represent different parts and limbs of the human body, 15-segment and simplified 9-segment models were developed (see Figs. 1 and 2). These models have been used to formulate various dynamical problems, including rotational stability under zero torque with limb manipulation, effects of a thrust misalignment, and optimum programming for extra-vehicular activity with a thrust-maneuvering unit.

Astrodynamics

Lunar-earth trajectories have been investigated by three students. One purpose of these studies was to compare approximate analysis methods, based on the sphere-of-influence concept, with more accurate trajectories obtained by numerical integration of the equations of motion. Another purpose was to investigate effects of the launch parameters, such as velocity, lunar longitude, and flight-path angle on the re-entry angle and velocity. Because the re-entry angle is extremely critical, an optimum set of lunar launch conditions was sought.

The first study used only the sphere-of-influence concept and treated the moon and earth as two fixed centers of force. It showed that the shallower the re-entry angle, the more sensitive the trajectory was to launch longitude and to burnout velocity. It also indicated that there was a particular launch longitude for which the sensitivity to velocity error was negligible. These results were suspect, however, because of the very restrictive initial assumptions.

The second study removed some of these restrictive assumptions on the sphere-of-influence technique by allowing the moon to travel in a circular orbit about the earth. The restricted three-body equations of motion for the return trajectories were derived and numerically integrated by using the Rünge-Kutta-Gill method. A brief note of explanation is in order to clarify the difference between these two approaches to the problem of lunar-earth trajectory calculations. The sphere-of-influence method of determining the trajectory of an orbiting body is based on the assumption that a complex n-body problem can be divided into a number of two-body problems with relatively simple solutions. Within the sphere-of-influence of one body, the forces of all other bodies are neglected. In the case of a three-body problem (e.g., an earth-moon-spaceship system), two two-body problems are considered and two solutions are obtained. The solutions are then matched or joined at the crossover point on the spheres-of-influence, resulting in a solution for the three-body problem.

In the earth-moon-spaceship system, the radius of the sphere-of-influence of the moon R is defined as the point where the ratio of the gravitational force of the moon to the gravitational force of the earth equals the ratio of the perturbing force of the moon to the perturbing force of the earth. The limit of this equality of ratios defines, very nearly, a locus which is a sphere of radius about the moon

$$R = D\left(\frac{\text{Moon Mass}}{\text{Earth Mass}}\right)^{2/5}$$

In the above equation, D is the distance, center to center, between the earth and the moon. This sphere is known as the activity sphere or sphere-of-influence of the moon. When the spaceship is within the sphere-of-influence, only the moon is considered as acting on the body, and the classic two-body or conic section equations can be applied. Outside the moon's sphere-of-influence, only the earth is considered as acting upon the spaceship, and again the conic section equations hold. These conic sections must be matched together at the crossover point.

For the numerical solution of the equations of motion in the more exact restricted three-body formulations of the problem, the earth and moon were assumed to have circular orbits about their common mass center. Both studies considered only trajectories in the plane of the earth-moon orbit. The second study revealed that numerical results obtained by the sphere-of-influence method did not agree closely with results obtained by numerical integration of the equations of motion, but that trends predicted by the sphere-of-influence method were confirmed by the equations of motion. Because of the extreme simplicity of the sphere-of-influence technique, it should be used initially to determine orders of magnitudes of numbers involved, and to determine areas for more detailed consideration. The second study also showed that there was an optimum lunar launch longitude, where errors in launch velocity had no effect on the re-entry angle. That is, if the returning spaceship were launched at that particular lunar longitude, the only critical guidance and control requirement would be to obtain the correct angle at burnout. This study also showed that the launch angle was the most critical parameter affecting re-entry angle and that no optimum launch longitude was found which minimized the sensitivity of re-entry angle to lunar launch angle.

The third study in this sequence considered out-of-plane launch parameters and searched for initial conditions that would again minimize sensitivity of re-entry parameters to errors in launch conditions. No improvement in launch conditions over the planar case was found.

Other astrodynamical studies have included the following investigations: the stability of motion near the Lagrangian points of the earth-moon system, including the effects of the sun on the motion (i.e., the restricted four-body problem); the stability of distant lunar orbits; periodic trajectories in cislunar space and possible orbits about Lagrangian points; and minimum fuel trajectories for thrust-limited rockets in an inverse-square force field. Future possibilities for research in astrodynamics are best illustrated by a doctoral dissertation currently being pursued by a faculty member on "Precision Trajectory Computations Using Constraints," and a dissertation only recently completed by another faculty member on "Relativistic Optimal Rocket Trajectories for Interstellar Travel." A brief discussion of these two studies is presented separately.

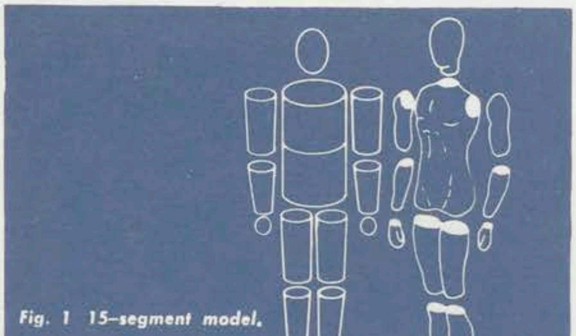


Fig. 1 15-segment model.

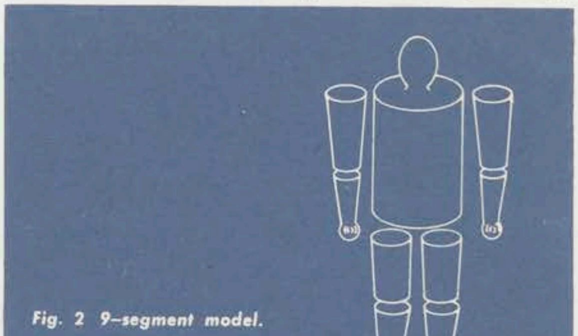


Fig. 2 9-segment model.

Structural Mechanics

An area of very active interest in the Department is structural dynamics, including studies of impact at various speeds ranging from water impact of thin-walled spherical vehicles at 20 ft/sec to impact and penetration of projectiles into plates at velocities from 1,000 to 10,000 ft/sec. All of these studies have significant applications in the fields of weapons, space vehicles, and space and lunar sciences. The study of water impact of spherical structures is directed toward making an accurate analysis of the dynamic loads on such vehicles, taking into account the elastic deformation of the structure. This study was performed in residence and included both an experimental and a theoretical investigation. Another study, performed on a cooperative basis at the Air Force Armament Laboratory, Eglin Air Force Base, Florida, was concerned with the penetration and damage mechanisms of bullets and shells in stressed-sheet panels. A joint research project with the Air Force Materials Laboratory, Wright-Patterson Air Force Base, using a light-gas gun to study hypervelocity impact effects on layered plates and rocks, is under way. This area of research is expected to grow considerably over the next few years.

Another area of research has been the analysis of complex structures using the concept of discrete-element idealization. A brief description of these studies is presented separately.

Discrete-Element Methods of Structural Analysis

J. S. PRZEMIENIECKI

Assistant Dean for Research and Professor of Mechanics

The discrete-element methods of structural analysis, developed for use on modern digital computers, are based on the concept of replacing the actual continuous structure by an equivalent model made up from discrete elements having known elastic and inertial properties that can be expressed in matrix form. The matrices representing these properties are considered as building-blocks that, when fitted together in accordance with a set of rules derived from the theory of elasticity, provide the static and dynamic properties of the actual structure. These new methods have become universally accepted in structural design and are providing a means for rapid and accurate analysis of complex aerospace structures under static and dynamic loading conditions.

The research work in this area within the Department of Mechanics has been quite extensive and has resulted in the publication of several papers in technical and scientific journals. Also, ten theses were prepared on topics ranging from purely theoretical investigations to experimental work intended mainly as verification of the matrix method of structural analysis.

The following specific investigations were undertaken by the students: experimental and theoretical determination of deflections of a heated truss representative of the X–20 orbital glider structure, effects of axial acceleration on the natural modes and frequencies of vibration of missile structures, experimental and theoretical determination of stresses in beam structures, stress diffusion in flat-plates, thermal-stress concentration in flat-plates with circular holes, natural modes and frequencies of vibration of skewed-plates, large deflections in diamond-

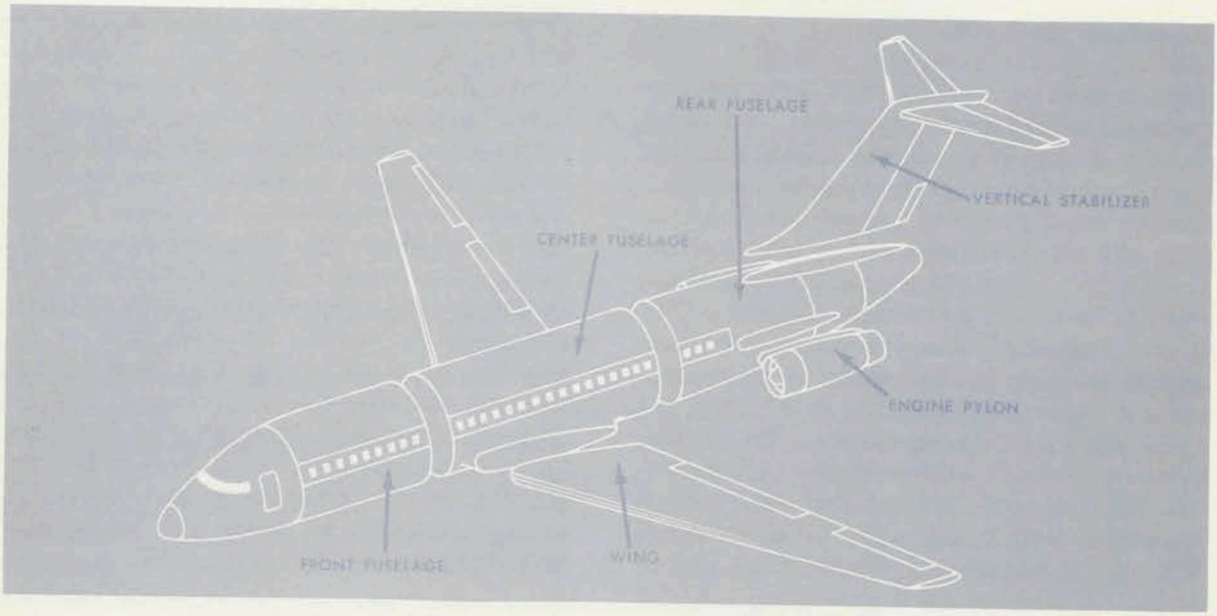


Fig. 3 Typical substructure arrangement of a medium-range transport aircraft.

shaped frames, general analysis of axisymmetrical shells, large deflection matrix force analysis of trusses and frames, and matrix displacement analysis of toroidal shells.

Faculty research work on discrete-element methods evolved naturally from the development of a course on matrix structural analysis, in which it became apparent that, because of significant gaps in the state-of-the-art, further development work was required. As an example, existing analysis programs could not accommodate large structures; consequently, matrix displacement and force methods of substructure analysis were developed.

A typical substructure arrangement of a medium-range transport aircraft consists of six structural components (substructures): wing; front, center, and rear fuselage; engine pylon; and vertical stabilizer (see Fig. 3). In the substructure method of analysis, stiffness or flexibility is determined for each substructure to permit treatment of each as a complex element for the partitioned structure. Once the displacements or forces on the substructure boundaries have been found, each substructure can then be analyzed separately under the action of known boundary displacements or forces. The substructure methods developed at AFIT have been used in industry for actual design analyses on a number of aerospace projects. In one application, these methods were also used in the design of a submarine.

Other research projects that have been carried out include the development of elastic and inertial properties for some basic elements, the determination of frequency-dependent stiffness and mass matrices for use in vibration analysis, and the stability of structures.

A highlight of this research endeavor was the convening of an international conference on "Matrix Methods in Structural Mechanics." Held at the School of Engineering, 26–28 October 1965, and sponsored jointly with the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, the conference was attended by over 200 engineers and scientists from the United States, Australia, Belgium, Brazil, Canada, England, Germany, and Holland. The proceedings of this conference have been published as an Air Force report (AFFDL TR 66–80).

Relativistic Optimal Rocket Trajectories for Interstellar Travel

G. M. ANDERSON, *Captain, USAF*
Assistant Professor of Mechanics

In a study on relativistic rocket trajectories, optimal control theory was applied to the one-dimensional relativistic rocket equations of motion to determine the characteristics of relativistic optimal minimum-time and minimum-fuel trajectories under constraints on the rocket thrust, both acceleration limiting and thrust limiting. Using various types of rockets and assuming zero final velocities, these results were used to examine the feasibility of interstellar travel. These analyses show that the relativistic optimal control laws are similar in form to those for the equivalent Newtonian problems. For the two minimum-time problems considered, relativistic effects result in smaller mass ratios, smaller flight times recorded on the rocket, and longer flight times recorded by an inertial clock at the origin than are predicted by Newtonian theory for given final positions. With specified final positions and flight times, the relativistic minimum fuel problems require smaller mass ratios than do the equivalent Newtonian problems. Assuming a maximum acceleration limit of about $1.0g$, a flight-time limit of 40 years, and a mass ratio limit of 10^4, the maximum distances that can be traveled on minimum-time interstellar trajectories with acceleration-limited rockets are limited by the mass ratio rather than by the flight time (as recorded on the rocket). For the minimum-fuel acceleration-limited rocket problem, these distances are limited by both the flight time and the mass ratio. The maximum distances that can be attained with thrust-limited rockets are limited by the flight time. Only photon rockets, with exhaust velocities approaching the speed of light, are capable of interstellar travel over long distances. Rockets using ideal nuclear fusion and fission as energy sources are capable of reaching only the nearest stars on minimum-fuel trajectories. Ion rockets do not have the capability of traveling interstellar distances. On these relativistic rocket trajectories, the timing of events seen by an inertial observer differs considerably from that seen by an observer on the rocket.

This study also revealed some interesting properties of Newtonian one-dimensional minimum-time trajectories of thrust-limited rockets. If the *initial* mass of the rocket is specified, the minimum-time trajectory to a specified final-position velocity requires continuous maximum-magnitude thrusting. However, if the *final* rocket mass is specified, the minimum-time trajectory has a coasting period. To get a given final rocket mass to a given final position/velocity state, the minimum-time trajectory with specified final mass generally results in a smaller flight time and a smaller mass ratio than does the specified initial mass case.

Further research in these areas will include investigation of minimum-time rendezvous for thrust-limited rockets in two and three dimensions, including gravitational and aerodynamic effects. Investigation of the characteristics of relativistic optimal interstellar trajectories and the possible application of these trajectories to interstellar travel will be continued to include two-dimensional analyses, the effect of interstellar drag, and the application of interstellar ramjets.

Manned and Unmanned Exploration of Space

S. W. JOHNSON, *Captain, USAF*
Associate Professor of Mechanics

Faculty and student research associated with manned and unmanned exploration of space and of the lunar surface may be listed under four main headings:

- Effects of the space environment on materials.
- Effects of gravity on the behavior of granular media.
- Problems associated with putting man in space.
- Problems in astrogeology and geophysics.

Effects of the Space Environment on Materials

The effects of vacuum and ultra-violet radiation on thermal control coatings of spacecraft are being studied with the cooperation of the Air Force Flight Dynamics Laboratory and the Air Force Materials Laboratory, both at Wright-Patterson Air Force Base. In another study, effects of vacuum on the strength-loss and weight-loss of balsa wood were determined in vacuum chambers at the Arnold Engineering Development Center, Tullahoma, Tennessee, and at the Aerospace Research Laboratories, Wright-Patterson Air Force Base.

Micrometeoroid impact on thin plates is now under investigation with the cooperation of the Air Force Materials Laboratory. The goal of this investigation is to determine the proportions of gas, liquid, and solid that make up the debris cloud which forms as a hypervelocity projectile penetrates a thin plate (see Fig. 4). Results of this study may be applied to the design of bumper plates which shield the main pressure-retaining structures of manned spacecraft and lunar shelters.

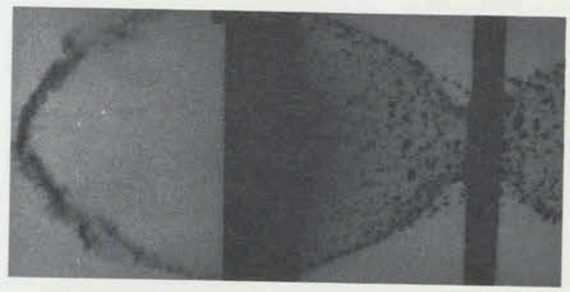


Fig. 4 Radiograph of a cadmium sphere impacting a cadmium bumper plate at 10,481 ft/sec. (The sphere moved from left to right; the plate on the right contains a 0.125-in. slit to permit the passage of a thin section of the debris cloud.)

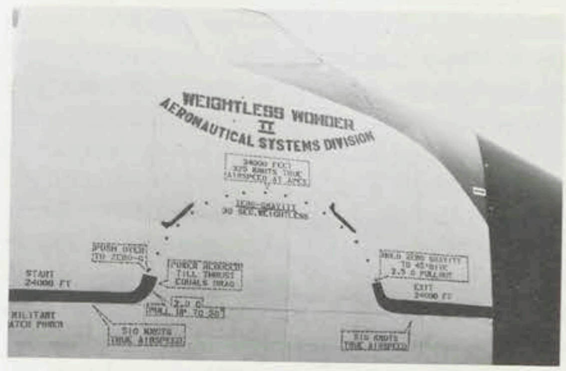


Fig. 5 Zero-g gravity aircraft used for research on effects of gravity on sizes of explosion craters.

Effects of Gravity on the Behavior of Granular Media

The effect of gravity on the behavior of soil on lunar and planetary surfaces will be different from the effect of gravity on soil on earth. Using aircraft belonging to the Aeronautical Systems Division (see Fig. 5), tests were conducted to determine the effects of gravity on the bearing capacity and explosion crater parameters of cohesionless soils. The aircraft used for this test can fly trajectories which allow the simulation of various values of gravity less than 1.0g for periods up to 30 seconds. Other investigations are under way in an effort to simulate the effects of micrometeoroid impact on soils and to determine the effects of gravity on the size of small craters produced by impact of hypervelocity projectiles (see Figs. 6 and 7). Results of these studies will be applied to the investigation of lunar and planetary surfaces and to the interpretation of data from crater counts taken from photographs of these surfaces.

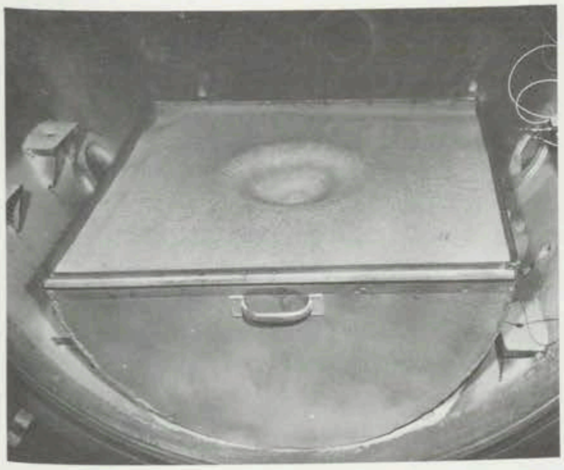


Fig. 6 Interior of a vacuum chamber used for research on effects of atmospheric pressure on the sizes of explosion craters.

Problems Associated with Putting Man in Space

Independent studies on problems associated with putting man in space include the feasibility of constructing an expandable space maintenance hangar, the excavation in lunar rock, the exploitation of lunar resources, and the design criteria for structures for a permanent lunar base. The study of the expandable space maintenance hangar was sponsored by the Air Force Flight Dynamics Laboratory. The review of techniques for excavation in lunar rocks associated with exploitation of lunar resources was suggested by the NASA Goddard Space Flight Center.

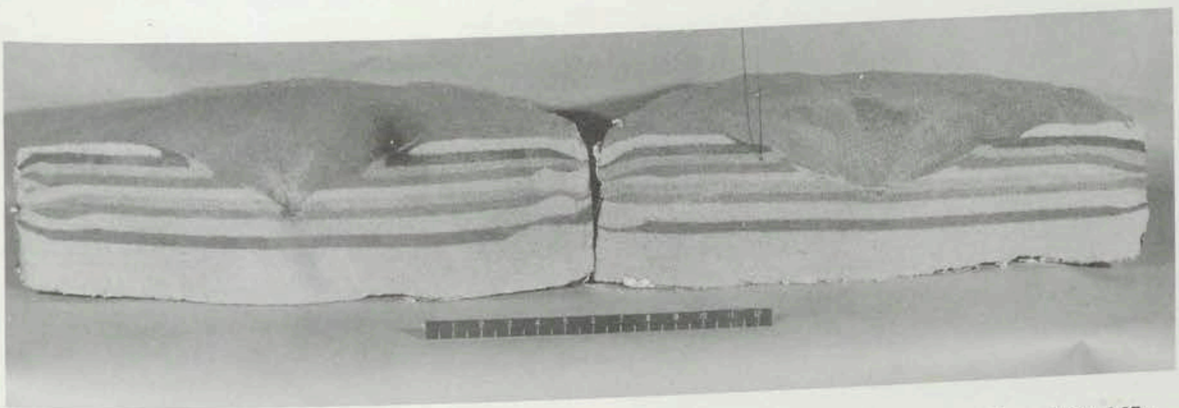


Fig. 7 Profiles of craters formed at (a) 2.5g and (b) 0.17g (lunar gravity).

Problems in Astrogeology and Geophysics

The projects in astrogeology and geophysics that have been completed or are under way include the formulation of an hypothesis to explain the origin of shatter cones, the use of neutron activation analysis techniques in determining the composition of rock, the cataloging of lunar domes and inquiry into their origins, and the effects of the impact of hypervelocity projectiles on rock. The development of neutron-activation analysis techniques to determine the composition of rock will require continuing effort. This work, which is being done at the Nuclear Engineering Test Facility, is to include the development of procedures for use in both major and minor element detection and in the calculation of quantities of such elements present in various rocks and minerals. One of the more significant soil-forming agents on the lunar surface may be the impact of meteoroids on rock. The effects of impact of hypervelocity projectiles on rock is being studied at AFIT in cooperation with the Air Force Materials Laboratory. Both macroscopic and microscopic effects are being considered for basalt targets and projectiles of various compositions. The United States Geological Survey Branch of Astrogeology is furnishing some assistance by supplying the target rock and reviewing the results.

Plans for Future Research

A project is also under way to develop an AFIT laboratory for the Graduate Space Facilities Program. This laboratory will contain a space simulation chamber capable of reaching 10^{-11} torr, petrographic microscopes for use in research and instruction, and supporting equipment for use in studies of the effects of the space environment on materials and the effects of vacuum on lunar soils.

Precision Trajectory Computation

J. L. KURZENBERGER, *Captain, USAF*
Instructor in Mechanics

Research in trajectory computation methods is mainly directed toward achievement of accurate high-speed digital computation with moderate-size computers to determine the trajectory of a space vehicle under the influence of small perturbing forces.

It has been common practice to express trajectory equations of motion in a rectangular cartesian reference frame with origin at the primary body. The most straightforward method is Cowell's, which is the direct integration of the equations of motion in terms of the cartesian coordinates. The computations are very simple, but because of the choice of reference frame, the variables must undergo large changes; consequently, computation step-size must be kept very small to prevent unacceptable accumulation of integration errors. To improve the computation accuracy, another method was devised by Encke. This method is a perturbation technique, which consists of integration of the perturbations from a reference conic trajectory.

In this method, an adjustment is made in the reference conic whenever the precision trajectory departs from it beyond preselected bounds. This method is used widely, since it does give a very substantial accuracy improvement. Penalty for this accuracy gain, however, is paid in terms of the extra computation required to determine the osculating conic and the needed reference-state vector. The total amount of computation required for a given accuracy can be comparable to that required with Cowell's method.

An even greater accuracy improvement is obtained if the equations of motion are written in terms of the elements of the osculating conic trajectory. This method permits large step-size in the computation; however, the resulting equations of motion are complex and contain a number of bothersome singularities and the results are obtained in terms of the instantaneous orbit elements, rather than in terms of vehicle coordinates. For these reasons, this method is seldom used for space-vehicle trajectory computations.

The method presently under investigation should provide sufficient accuracy, and, at the same time, should alleviate some of the problems previously mentioned. By using a combination of *constraint* equations, such as angular momentum and the components of the Rünge vector, it appears possible to obtain a set of slowly varying parameters which would be constants if the perturbing forces were removed. The solutions of these problems, which employ large step-size computations, can be obtained directly in terms of vehicle coordinates and velocities that can be used to display a trajectory without further processing.

Metallurgy

J. R. MYERS
Associate Professor of Metallurgy

For many years the advanced concepts for modern weapon systems were not limited by the availability of materials. However, with the advent of the space age, this freedom in design changed drastically as "off-the-shelf" materials were no longer satisfactory for meeting the requirements of the designer. It then became obvious that increased efforts in materials research were needed.

In the summer of 1962, the Metallurgy Section, Department of Mechanics, initiated a capability-improvement program for the purpose of providing adequate facilities for studies in advanced materials research. Since that time, the faculty has conducted numerous projects, primarily in corrosion and metallurgical thermodynamics, all oriented toward the solution of current and future Air Force problems in materials research. Studies in corrosion and metallurgical thermodynamics were selected because basic data in these areas were considered important to the applied research efforts being conducted throughout the country. Furthermore, the academic backgrounds of the faculty specifically qualified them for work in these scientific disciplines. Concurrent with this effort, a Graduate Materials Engineering Program was also established.

In conducting research work in metallurgy, AFIT personnel worked closely with scientists and engineers at the Air Force Materials Laboratory and Aerospace Research Laboratories, Wright-Patterson Air Force Base. This relationship enabled the faculty and students to gain increased knowledge through exposure to research conducted by the laboratories.

Since 1962, the AFIT metallurgy research program has resulted in the publication of over twenty-five papers in recognized technical journals. Some of the more important basic programs are highlighted in subsequent sections of this report. These include studies in stress-corrosion cracking, oxidation, metallurgical thermodynamics, anodic polarization, and phase-diagram determinations.

Stress-Corrosion Cracking

Although tensile stress (either applied or residual) or certain corrosive environments alone have no deleterious influences on materials, it is well known that their combined effects have resulted in premature cracking failure. For example, numerous corrosion-cracking service failures have been experienced in USAF aircraft systems, including the landing gears and the actuators and "B" nuts in the hydraulic systems.

Since research to date has not provided a complete understanding of the basic fundamentals of corrosion cracking, the AFIT Metallurgy Section has conducted extensive studies on the stress-corrosion cracking of austenitic stainless steels exposed to chloride-containing, aqueous environments (boiling 42 wt. % $MgCl_2$ solution). These studies were conducted to determine the existence of a threshold stress (i.e., a stress value below which cracking will not occur in a reasonable time period) and the effect of grain size and cold work on this type of corrosion.

The results of corrosion cracking, using tests with laboratory-annealed Types 302 and 316 austenitic stainless steels, revealed that, as the applied tensile stresses were increased the time-to-failure decreased, and that all cracking was transgranular. Cracking did not occur at an applied stress of 5,000 psi until the cross-sectional area of the wire specimens had been reduced considerably by general corrosion (see Fig. 8). The results also indicated that the introduction of small residual tensile stresses in the specimens eliminated the existence of a threshold stress for these materials. The significance of these results was that, since residual stresses will almost always exist in service, the designer cannot eliminate the occurrence of stress-corrosion cracking by reducing the applied stress below the threshold value.

In a follow-on program, Type 302 austenitic stainless steel was cold-worked to quantitatively investigate the effect of this variable on cracking behavior. It was found that the 10 per cent cold-worked specimens exhibited the shortest time-to-failure over the applied tensile-stress range studied (10,000 to 30,000 psi). The 30 per cent cold-worked material had the maximum resistance to stress-corrosion cracking. The short times-to-failure recorded for the 10 per cent cold-worked material were attributed to the introduction of large amounts of localized

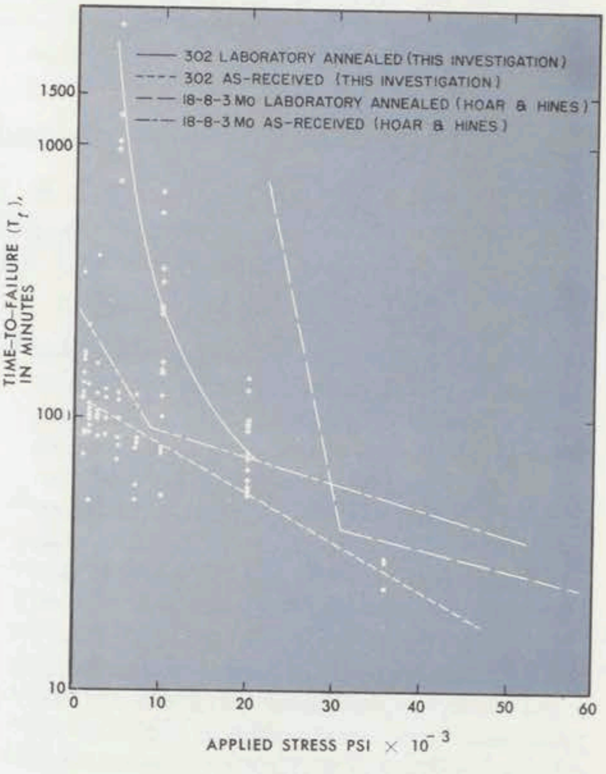


Fig. 8 Effect of applied stress on time-to-failure for Type 302 austenitic stainless steel exposed to boiling 42 wt. % $MgCl_2$ solution. (Note that a threshold stress exists for laboratory-annealed material, but does not exist for the as-received material which contained small residual tensile stresses.)

residual stresses in the annealed material (without any metallurgical phase changes occurring) by the cold-working process. The longer times-to-failure associated with the more heavily cold-worked material were explained by the transformation of relatively unstable austenite to "quasi-martensite." From this research, it was also determined that crack-propagation rates, nearly independent of applied stress, were greatest for the 10 per cent cold-worked material.

Additional studies were conducted to provide further proof to the belief that residual tensile stresses are deleterious and the austenite-to-"quasi-martensite" phase transformation is beneficial to the cracking of austenitic stainless steels. Type 309 austenitic stainless steel was selected for investigation because the chemistry of this stable alloy is such that it will not transform to "quasi-martensite" by cold-working. Results of this investigation clearly established that increasing the amount of cold-work in the absence of "quasi-martensite" formation (and, therefore, increasing the amount of residual tensile stresses) reduced the times-to-failure for all of the applied stresses studied.

The research of earlier investigators suggested that a grain-size dependency existed for the initiation of stress-corrosion cracking in austenitic stainless steels. Type 302 austenitic stainless steels of two widely different grain sizes were studied to further the understanding of any grain-size effect on corrosion cracking. The stress-corrosion cracking behavior of this alloy was determined to be grain-size dependent, and the decreased resistance to cracking observed for the larger grain-size material was associated tentatively with a decreased incubation period (i.e., the period required for crack initiation). A dislocation model was proposed to explain the crack–initiation period.

At the present time, further research is being conducted to quantitatively determine the effect of grain size on the incubation period and crack-propagation rate of Type 302 austenitic stainless steel.

Oxidation of Pure Cobalt and Nickel-Base Superalloys

Because of conflicting data reported in the literature, the oxidation of high-purity cobalt (99.999% Co) was investigated at selected partial pressures of oxygen over the temperature range 950°–1,250°C by using a thermogravimetric technique. It was determined that the oxidation of cobalt exhibited parabolic kinetics with the parabolic rate constant closely represented by the expression

$$k = 6.0 \times 10^{-2} \, (p_{O_2})^{0.35} \, e^{-37,100/RT}$$

where k is the rate constant (gm²/cm⁴ sec), p_{O_2} is the oxygen partial pressure (atm), R is the gas constant (1.987 cal/mole/°K), and T is the absolute temperature (°K). The experimentally determined rate of oxidation agreed within 3–9% of the oxidation rate when calculated by Wagner's rate equation and the self-diffusion coefficient of cobalt in cobaltous oxide.

Oxidation studies of René 41 and thoriated nickel filaments were conducted to provide basic data for other USAF laboratories considering the use of 0.010-inch and 0.020-inch diameter wires for advanced space systems and metal-reinforced ceramic composites.

Thoriated nickel was oxidized in air (p_{O_2} = 0.020 atm) over the temperature range 1,600 – 2,000°F. Analysis of the data revealed that the oxidation of this material obeyed both a cubic and a parabolic rate law, depending upon the exposure time and temperature, according to the expression $(\Delta W/A)^x = kt$ where $\Delta W/A$ is the weight-gain per unit area, k is the rate constant, t is the time, and x is the exponent describing the rate law. A log-log plot of weight-gain (mg/cm²) vs. time (min.) revealed that parabolic oxidation rates (slope = ½) were obtained at 1,800°F and 2,000°F for both diameters of filaments and at 1,700°F for 0.010-inch diameter filaments. A reliable oxidation rate analysis could not be determined at 1,700°F for the 0.020-inch diameter material; however, results suggested a quartic rate (slope = ¼) followed, with time, by a parabolic rate. At 1,600°F, oxidized 0.010-inch and 0.020-inch diameter filaments appeared to follow a cubic rate law (slope = 1/3). The rate constant for the parabolic oxidation of thoriated nickel (TD nickel) filaments obeyed an Arrhenius relationship with an apparent activation energy of approximately 39.4 kcal/mole (see Fig. 9).

Oxidized 0.010-inch diameter Rene′41 filaments exposed at 1,600°, 1,700°, 1,800°, and 2,000°F appeared to exhibit an initial quartic oxidation rate followed by parabolic behavior. The activation energy obtained during parabolic oxidation was determined to be 41.4 kcal/mole (see Fig. 9).

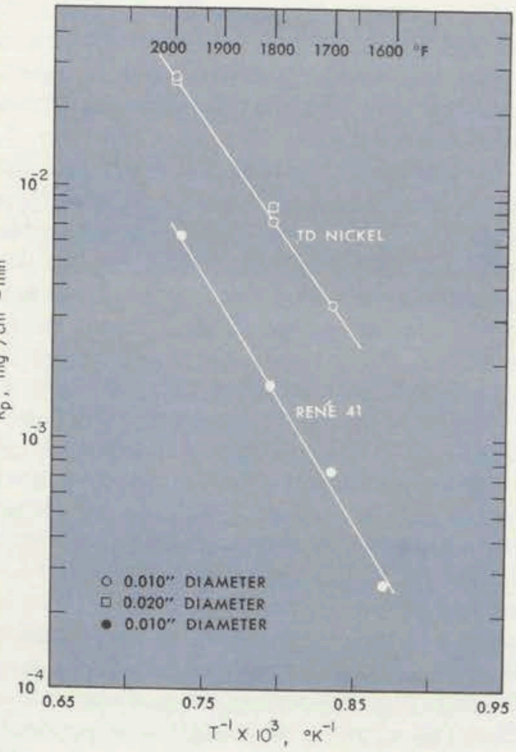


Fig. 9 Effect of temperature on the parabolic rate constant (Arrhenius plot) of TD-Nickel and René 41 filaments exposed to air.

Phase Diagram Determinations

Molten salt systems have been analyzed since World War II to investigate the possibility of their use as coolants in nuclear reactors. In a study conducted by this Department, thermal analysis and X-ray techniques were used to determine the phase diagram of the lead molybdate/bismuth molybdate system. The diagram was found to be a simple eutectic type with a eutectic at 11 mole per cent lead molybdate and 634°C. A maximum solid solubility of 6 mole per cent was established at the lead molybdate end of the diagram. Solid solubility at the bismuth molybdate end of the diagram appeared to be quite limited and possibly nonexistent. These newer results differed significantly from those reported in the literature in the 1920s.

The TiAl phase boundary at 2,325°F was determined for the Ti-Al-Zr ternary system as part of an investigation directed to improving the ductility of this high-temperature, oxidation-resistant intermediate phase. This research was stimulated by the results of others who inferred that small additions of zirconium could improve the ductility of TiAl and would permit the use of this material for a variety of re-entry vehicle applications. They theorized that the c/a ratio of face-centered tetragonal TiAl could be reduced by the addition of zirconium so as to approach unity. However, contrary to these predictions, it was established in an AFIT research project that the c/a ratio did not approach unity. The c/a ratio at the maximum solubility limit of zirconium within the single phase was 1.025, and it increased slightly as the zirconium substitutionally replaced the titanium within the TiAl lattice.

Metallurgical Thermodynamics

Reliable vapor-pressure data for metals and elements contained in advanced alloy systems are required for determining the behavior of these materials when exposed to space environments (vacuum) at elevated temperatures. In addition, the information generated from these data provides basic thermodynamic properties (e.g., chemical activities, enthalpies, and entropies) which can be used in obtaining a better understanding of a variety of metallurgical phenomena, including diffusion, phase transformation, and nucleation. All thermodynamic studies conducted at AFIT have used the Knudsen effusion technique.

The vapor pressure of electrolytic, high-purity solid chromium was determined over the 1,560°–1,800°K temperature range because no data were available in the literature for temperatures above 1,675°K. From these data, it was determined that the vapor pressure of solid chromium (over this temperature range) could be represented by the expression

$$\log P \text{ (atm)} = -21{,}580/T + 8.01$$

Concurrently, the value of $\Delta H^\circ_\circ$ (heat of sublimation at absolute zero) for each test temperature was calculated by means of the third law of thermodynamics. The overall average value of $\Delta H^\circ_\circ$ was determined to be 94.8 ± 0.4 kcal/mole.

Because of the suggested lack of precision in the data reported by earlier investigators, the chemical activities of cadmium and magnesium in binary Mg-Cd alloys were determined for selected temperatures varying from 571°–697°K. The vapor pressure of pure solid cadmium (99.99+% Cd) was determined first over the selected temperature range and was found to obey the expression

$$\log P \text{ (mm Hg)} = 9.007 - 5{,}919/T$$

An average value for the standard heat of sublimation at 298°K (ΔH°_{298}) was calculated to be 26.83 ± 0.07 kcal/mole, which was in good agreement with values reported by others. When data for the vapor pressure of cadmium over cadmium-magnesium alloys were used, the chemical activities of cadmium were determined at 573°, 598°, and 623°K. These activities exhibited negative deviation from Raoult's law at all compositions. The chemical activities of magnesium were calculated by the Gibbs-Duhem equation and also were found to exhibit negative deviation at all compositions.

In another study, the equilibrium vapor pressure of oxygen-free high conductivity liquid copper (99.98% Cu) in the temperature range 1,475°–1,707°K was determined to obey the relationship

$$\ln P \text{ (atm)} = -39{,}129/T + 14.203$$

The average value of the heat of sublimation at absolute zero ($\Delta H^\circ_\circ$) was found to be 80.807 ± 0.190 kcal/mole. These thermodynamic values for liquid copper were considered significant since they were the first data above 1,563°K obtained by the Knudsen technique.

After obtaining the thermodynamic data for liquid copper, the thermodynamic properties of copper-platinum alloys were determined to provide basic input to diffusion research being conducted at the Air Force Materials Laboratory. Vapor pressures of copper over five copper-platinum alloys were determined within the temperature range 1,540°–1,680°K (see Fig. 10). The chemical activities of copper at all compositions exhibited negative deviation from Raoult's law, but were found to approach ideality as the temperature was increased. Chemical activities of platinum at all compositions also exhibited negative deviation. The integral free-energies of formation of the alloys varied smoothly with composition and were found to have a minimum value of 4,200 cal/mole at about 55 at.% copper. Integral enthalpies were found to be negative with a maximum value of approximately 3,400 cal/mole. The excess free energies were found to be negative, with the minimum value occurring at approximately 55 at.% copper—the composition of the congruent maximum of the large, low-temperature, ordered phase. Integral excess entropy values were determined to be small and negative.

Investigations of the thermodynamic properties of additional metals and selected alloy systems continue to be conducted. These include studies of Mo-Cr, Fe-V, Co-Pt, and Cb-Ti binary alloys.

Anodic Polarization Behavior

A metal or alloy is said to be *passive* when it does not corrode in an environment where thermodynamic theory predicts it should. Although several theories have been proposed to explain passive behavior, additional studies are needed before a complete understanding of this surface phenomenon can be realized. One of the most important means of studying passivity involves the determination of potentiostatic anodic polarization (potential vs. current) curves for selected metal/environment combinations (see Fig. 11). An analysis of these data permits a better understanding of the active, passive, and transpassive behavior of a metal or alloy in a given electrolyte. The completed research included studies of Ni, Cr, and Co, and the Ni-Cr, Ni-Co, and Co-Cr binary alloy systems, and the polarization behavior of selected low-alloy steels.

Studies of Ni, Cr, and the Ni-Cr system revealed that, except for pure nickel in 20N acid, all compositions exhibited an active-to-passive transition in all environments used (1, 5, 10, and 20N H_2SO_4). A minimum in the critical current density vs. the percentage of chromium curves was established at 90–95 wt.% Cr. The passive current density decreased with increasing chromium content over the composition range 0–33 wt.% Cr. Concurrently, corrosion potentials, Tafel slopes for anodic dissolution and oxygen evolution, and passivation potentials were determined.

Metallographic examination of anodically polarized nickel and chromium after long-time exposure at selected active, passive, and transpassive potentials in 1N H_2SO_4 at 25°C revealed significant surface topography differences. Etch pits, present only in the transpassive state, supported the belief that "active patches" are generated in the passive films of these metals at potentials more noble than the passive region. The effect of temperature on passive nickel exposed to 0.5, 1, 5, and 10N H_2SO_4 over the range 25°–95°C revealed that an inflection temperature (T_i) existed for this material. Above T_i, "active patches" appeared and resulted in a breakdown of the passive film. Since T_i was dependent upon acid concentration (as was the activation energy for film dissolution), Seeger's activation energy for crystallization of a very thin pseudomorphic film and Kramer's exo-electron emission temperature (proposed by earlier investigators) were discounted as a means of fully explaining the generation of "active patches" in a passive film.

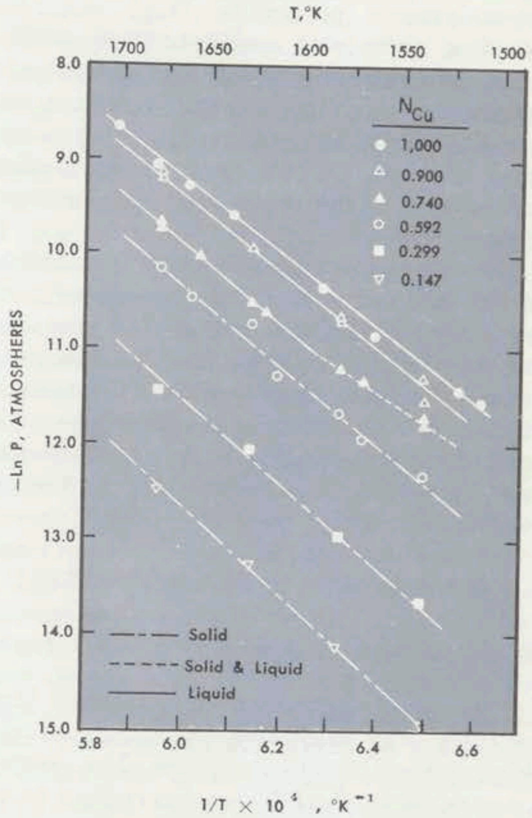


Fig. 10 Vapor pressures of pure copper and copper over copper-platinum alloys.

During a study of Ni, Co, and Ni-Co alloys, it was established that only pure nickel and alloys containing 52 wt.% or more nickel exhibited an active-to-passive transition in 1N H_2SO_4. As the acid concentration was increased to 5 and 10N, the nickel content required to establish an active-to-passive transition was increased to 63% and 100%, respectively. Pure cobalt and nickel-cobalt alloys not exhibiting true passive behavior did reveal marked secondary passivation at potentials just before oxygen evolution. Critical current densities, passive current densities, and Tafel slopes for anodic dissolution and oxygen evolution were determined and correlated with acid concentration and metallurgical structure.

Studies of the Co-Cr binary system revealed that all specimens, except for pure cobalt and the 95 Co/5 Cr alloy, had an active-to-passive transition in 1, 5, and 10N H_2SO_4. The marked secondary passivation exhibited by pure cobalt and 5 wt.% Cr alloy was attributed to adsorbed oxygen, and the predominantly transpassive electrochemical process for specimens containing 15 wt.% or more chromium was chromate formation. Critical current densities and passive current densities decreased as the chromium content was increased to 30 wt.%. Corrosion potentials and Tafel slopes were evaluated and discussed in terms of acid concentration and the metallurgical structure of the Co-Cr system.

In a later study, the anodic polarization behavior of selected low-alloy steels (AISI 1045, 4047, 4140, 4340, and 5140) were determined at 25°C in acid concentrations varying from 0.01 to 5N H_2SO_4. It was shown that all steels in these environments have identical behavior, and the anodic behavior of mild steel is not affected by the small alloying additions. The data were considered to be significant to engineers concerned with the anodic protection of process equipment exposed to H_2SO_4 environments. The results should also assist in the development of corrosion-resistant, low-alloy steels having desirable mechanical properties.

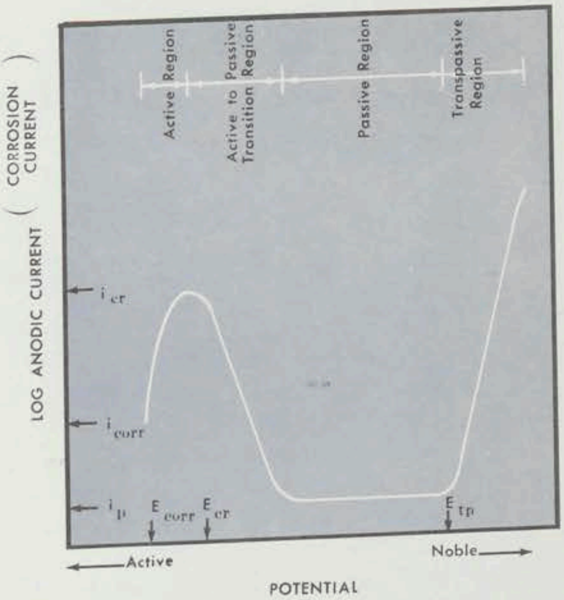


Fig. 11 Generalized potentiostatic anodic polarization curve for metal or alloy exhibiting active, passive, and transpassive behavior.

At the present time, research is being conducted to determine the anodic and cathodic polarization behavior of Fe-Si, Fe-Co, and Ti alloys in sulfuric acid environments. These data should assist in predicting the corrosion behavior of metals without the need for long-time corrosion testing.

Other Metallurgical Research

In addition to those programs already described, other research studies have been conducted on (1) the corrosion behavior of beryllium exposed to various aqueous-chloride environments, (2) the corrosion of high-temperature superalloys by molten boron oxide, (3) the internal oxidation of Au-In alloys, (4) the stress-corrosion of beryllium alloys, (5) creep of polycrystalline in sea water, (5) creep of polycrystalline nickel wire, (6) diffusion in Cb-Zr and Mo-Ti binary alloys, and (7) internal friction.

physics

L. S. PEDROTTI
Head, Department of Physics

Faculty research in the Department of Physics during the past five years has been conducted in the general areas of weapon effects, solid state physics, plasma physics, bioengineering, computational physics, and neutron wave propagation in nuclear systems.

In most of the studies, research has been conducted in support of technical problems generated by current Air Force needs. In such studies the research has usually been carried out in Air Force laboratories located at Wright-Patterson Air Force Base, but not infrequently at Air Force laboratories located elsewhere in the country. More often than not, these studies have been undertaken as team efforts of laboratory scientists, Department professors, and AFIT graduate students. In each instance, the latest and most advanced research facilities at the Air Force laboratories have been made available to the team. Such equipment has included a 10 megawatt thermal reactor, a 2 Mev Van de Graaff accelerator, a 15,000 curie cobalt-60 gamma source, a KC–135 zero-*g* aircraft, a six-inch bore gas gun, vacuum ultra-violet spectrometer, and a CDC 6600 computer.

In other studies within the same general areas, research projects have been initiated largely within AFIT and have been pursued within the School as a faculty-student team effort. In such instances, the research projects were centered around the research facilities available within the laboratories of the Department of Physics. Presently, such research facilities include a light-water moderated subcritical assembly, a 150 kilovolt Cockcroft-Walton positive ion accelerator, a Mossbauer spectrometer, several 400-multichannel pulse-height analyzers, a Bausch and Lomb two-meter grating spectrograph, an 8-channel physiological monitoring system, a surgery laboratory for small animal research, several telemetering Doppler and gated sine wave blood-flow meters, and a variety of radiation detection and counting equipment.

In addition to the research work previously mentioned, which is mainly faculty oriented, a substantial amount of research has been carried on by graduate students in a cooperative work-study program developed in conjunction with Air Force laboratories. Under this program, a student in either the Graduate Nuclear Engineering or Graduate Space Physics Program spends six months of his academic tour on a full-time, on-site assignment with a participating Air Force laboratory. His research effort, supervised jointly by a laboratory scientist and an AFIT professor, is directed toward the solution of a problem of immediate interest to the laboratory. Such a cooperative arrangement between a graduate student and a laboratory represents six months of highly motivated research work for the laboratory and a like period of productive academic growth for the student.

The magnitude of the research work carried out under this program with the Air Force laboratories during the past five years has been significant. Since 1962, a total of 140 graduate students have taken part in the cooperative work-study program in nuclear engineering and space physics. This represents the equivalent of 70 man-years of rearch work. Twelve major Air Force laboratories participated in the cooperative program—nine at Wright-Patterson Air Force Base and three at other locations throughout the country. The nine research facilities at Wright-Patterson include the Aerospace Medical Research Laboratory, Aero Propulsion Laboratory, Aerospace Research Laboratories, Avionics Laboratory, Flight Dynamics Laboratory, Foreign Technology Division, Materials Laboratory, Nuclear Engineering Test Facility, and the Radiation Laboratory of the USAF hospital. The other three include the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico; the Air Force Cambridge Research Laboratories, Bedford, Massachusetts; and Space Systems Division, El

Segundo, California.

It is also worthwhile to mention that several members of the faculty of the Department of Physics have become so closely associated with on-going research projects at several Air Force laboratories that a significant share of their research efforts has been conducted largely in the laboratory working directly with the laboratory scientists and technicians. This has been especially true in the study of optical and electrical properties of II–VI semi-conductor compounds at the Aerospace Research Laboratories and in the study of neutron and photon transport problems in thermonuclear environments with the Air Force Weapons Laboratory. These studies as well as others being conducted by the faculty of the Department of Physics are discussed in more detail in separate contributions.

Neutron Wave Propagation in Nuclear Systems

R. S. BOOTH, *Lieutenant, USAF*
Assistant Professor of Physics

The study of nuclear reactor dynamics is based on the introduction of some known excitation of the neutron density function into a given nuclear assembly and measurements of the subsequent response of the neutron density function. From this input-output relationship, the reactor physicist extracts information which he then compares with theoretical models.

A very accurate and recently revised technique for studying reactor kinetics is the neutron wave experiment. In this context neutron waves do not refer to the matter waves associated with the individual neutrons; rather, they refer to the collective behavior of the neutron density function. The essential point of the neutron wave experiment is the location of the neutron source at an external boundary of the assembly. The time-dependence of the neutron source is often selected to be sinusoidal as a matter of convenience, but any time-function which can be Fourier-analyzed is acceptable.

Placement of a modulated source of neutrons at one boundary of a nuclear assembly creates a disturbance which can be analyzed in terms of wave components propagating from this source with frequency-dependent phase shift and attenuation factors. The importance of the neutron wave experiment is based on the fact that these two independently measurable quantities are strongly dependent upon the diffusion, scattering, and thermalization properties of the assembly. Thus accurate determinations of physical constants and severe tests of theoretical models are possible through an experimental determination of the frequency-dependent dispersive properties (dispersion law) of the system.

The research in neutron wave propagation at AFIT has so far been restricted to theoretical investigations. Predictions of propagation of neutron waves in both thermal and fast systems have been made by using space-dependent, energy-dependent, and time-dependent diffusion theories. This research has been accomplished in close cooperation with members of the Nuclear Engineering Department of the University of Florida, where the study of neutron wave propagation in this country first originated.

Experimental data have been obtained by researchers at the University of Florida. Thus far, experiments have been limited to thermal systems. In the near future, experiments with fast systems will also be conducted. A comparison of the theoretical work done at AFIT and the University of Florida with the experimental results of work done at the University of Florida has verified that the neutron wave technique is a very accurate method for measuring reactor parameters.

The research on neutron-wave progagation is still in its formative stages. The applications of this research to both fast and thermal systems lie in the fields of reactor safety and in the development of an inexpensive and accurate way of determining reactor parameters.

Neutron Particle Transport

C. J. BRIDGMAN
Associate Professor of Physics

Neutron and photon transport calculations for nuclear reactors and nuclear weapons have been carried out in the Department of Physics in the past several years. These studies involved solution of the Boltzmann transport equation by diverse methods requiring the use of large digital computers. Recent reactor-oriented studies may be divided into three categories. The first of these involved energy-dependent, neutron spectra calculations in infinite media as determined in part by the moments expansion of the Boltzmann equation. This work led to a digital computer code for the calculation of neutron group cross-sections. This code was especially written for university use and small computers. The second category of reactor studies consisted of neutron flux and criticality determinations on nuclear rockets and space auxiliary nuclear power supplies. Systems investigated included cavity or gaseous core rocket reactors; solid core, fast, rocket engines; and nuclear, direct-energy-conversion, auxiliary systems. Carlson's S–N approximation to the Boltzmann equation was used in all of these studies. This work was carried out under sponsorship of the Aerospace Research Laboratories and Foreign Technology Division, both at Wright-Patterson Air Force Base. The third category of reactor calculations employed the multi-energy group, neutron-diffusion approximation of the Boltzmann equation to predict the burn-up and the kinetic response of AFIT's 10 Mw reactor at the Nuclear Engineering Test Facility, Wright-Patterson Air Force Base.

Another area studied was the effects of nuclear weapons. Specifically, several simple models describing the transport of photons from a nuclear weapon in the atmosphere and in re-entry vehicles were investigated. These investigations are contributing to the development of reliable, approximate methods for routine calculation. Neutron transport calculations in air are also being investigated using the consistent P–1 approximation to the Boltzmann equation (the telegrapher's equation). Future plans include the application of the S–N approximation to both neutron and photon problems. The nuclear weapon effects calculations are being carried out in support of research programs of the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, and are motivated by the possibility of perfecting calculational methods which are more economical than the Monte Carlo methods now in wide use.

Vacuum UV Reflectivity and Electron Beam Spectroscopy of Solids

R. L. HENGEHOLD
Associate Professor of Physics

When considering any material for potential application, it is necessary to have some knowledge of the electron energy-level structure of that material. In solids, this energy-level structure consists of a series of energy bands (the so-called band structure of the solid), the lower bands containing bound electrons, and the topmost or conduction band containing essentially free electrons. All of these electrons can be excited by external stimuli, such as impinging photons or electrons. Those electrons in the lower-lying bands can suffer single-particle excitations and move up into higher bands (interband transitions). On the other hand, those electrons in the conduction band can be excited collectively and set into oscillations (plasma oscillations). A better knowledge of both of these excitation phenomena is important to a better understanding of the basic properties of the solids. The experimental solid-state physics program at AFIT includes a study of these phenomena. The techniques being used in this study are vacuum ultraviolet reflectivity and electron-beam spectroscopy. The particular solids being studied are the II–VI semiconducting compounds (single crystal or platelet form) and various selected metals (thin films), such as Al, Zr, and Ti.

In recent years the method of vacuum ultraviolet reflectivity has been a very fruitful means of determining the energy-band structure of semiconductors. In this method, light obtained from a strong ultraviolet source, such as a hydrogen discharge, is sent through a vacuum ultraviolet monochromator and reflected from the surface of the semiconductor under investigation. The intensity of this reflected light, as well as that of the incident light, is measured with a photomultiplier tube. The ratio of reflected intensity to incident intensity is then calculated at each wavelength. This ratio, defined as the reflectivity, is then plotted as a function of wavelength (or photon energy), and the resulting curve is found to contain a series of peaks. Each peak so obtained can be associated with the excitation of an electron in the solid; thus, one can infer the energy band structure. Furthermore, the energy required for the excitation of a plasma oscillation can be found through the use of a mathematical technique called a Kramers-Kronig analysis. Although this method is very useful, it is limited to the energy range of approximately 3 to 12 ev because of the sources presently available. At present, the faculty and students are conducting experiments in the Solid State Laboratory of the Aerospace Research Laboratories (ARL). In these experiments, measurements are being made on II–VI compound alloy systems, particularly CdSSe and CdZnS, to determine the effect of alloying upon the band structure of the pure compound. These measurements are being made at both room temperature and 77°K by the use of both polarized and nonpolarized light.

A second method of examining electron excitations, particularly the plasma oscillations, is that of electron-beam spectroscopy. This technique can be applied by using electrons transmitted through a thin film sample or reflected from the surface of a bulk sample. In electron-beam spectroscopy, a beam of monoenergetic electrons is allowed to interact with the sample under investigation. As a result of this interaction, electrons in the incident beam lose energy to the electrons in the sample; thus, the reflected beam contains electrons of various energies. Using a velocity analyzer and an electron multiplier detector, an energy analysis of the reflected beam can be made which yields a curve of the number of electrons vs. energy lost. Such a curve will exhibit peaks at those energies required for excitation of the electrons in the solid. Some of the peaks can be associated with plasma oscillations and some with interband transitions. Although this technique is not nearly as accurate as the light-reflectivity method for low-energy excitations (<10ev), it is quite accurate and considerably less difficult to employ at energies greater than 10 ev. The method of electron-beam spectroscopy is, therefore, complementary to that of vacuum ultraviolet reflectivity. At present, electron-beam spectroscopy with reflected electrons is being employed in the AFIT Physics Laboratory to study II–VI compound single crystals provided by ARL. The Department also has equipment available for conducting electron-beam spectroscopy analysis with transmitted electrons. This equipment was designed and built to provide an ultra-high-vacuum atmosphere and *in situ* evaporation of thin films (see Fig. 1). In this way, thin metal films can be produced with very clean surfaces, and the transmission technique can be used to obtain the electron excitation spectra of these metals and to determine the effect of sample surface condition. A study of aluminum films has been completed, and the surface effect on the plasma oscillations in aluminum has been investigated (see Fig. 2). This work is now being extended to other metals, particularly to those with more reactive properties than aluminum.

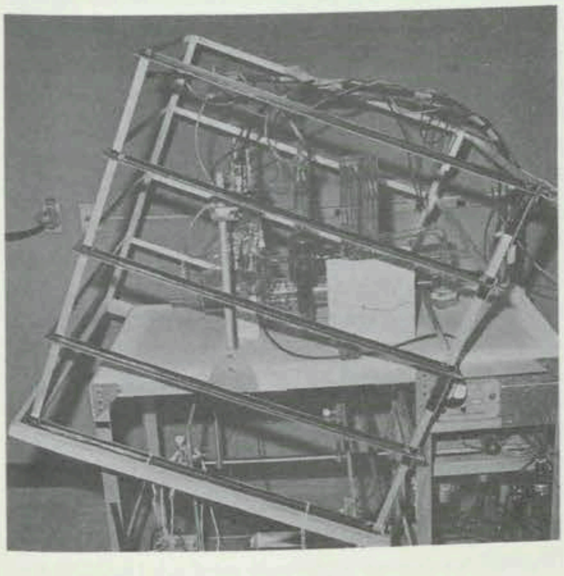


Fig. 1 Experimental ultra-high vacuum apparatus for electron beam spectroscopy studies of thin films.

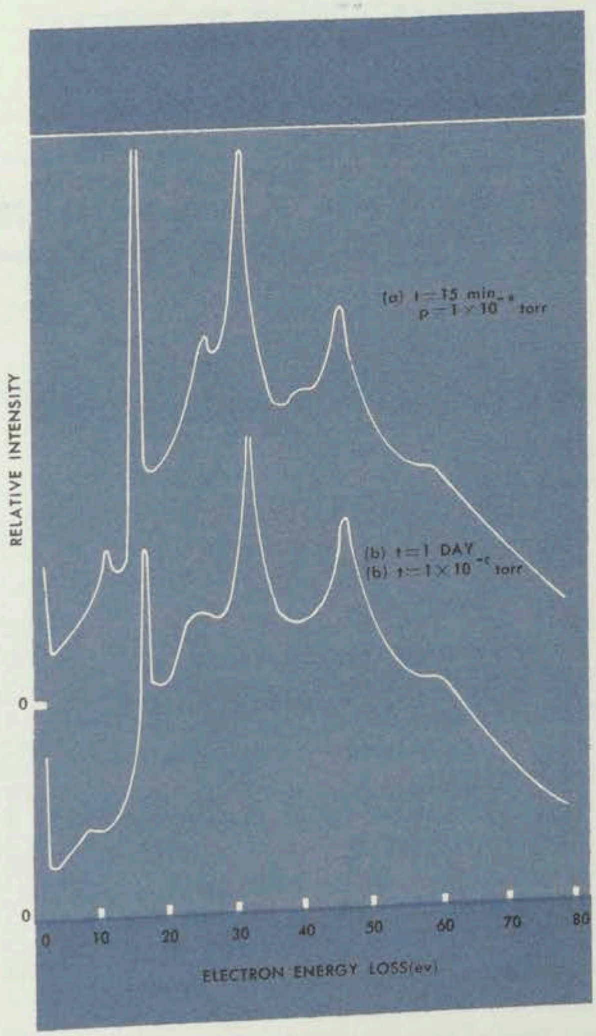


Fig. 2 Electron energy loss spectra of aluminum. Curve (a) shows the spectrum of newly-evaporated film having a clean surface. Curve (b) shows the changes that occur as this surface becomes contaminated.

Experimental Physics

G. JOHN
Associate Professor of Physics

The work in experimental physics is somewhat diverse since it is derived from projects of interest to several of the laboratories at Wright-Patterson Air Force Base. In the main, the projects were concerned with physical measurements and instrumentation.

Several projects that are now under way or have been completed (in most cases with student assistance) include (1) measurement of vapor pressures and heats of sublimation and vaporization of metal chelates, (2) construction and testing of apparatus for the determination of fluorescence lifetimes of nanosecond magnitude, (3) development of routine methods for neutron activation analysis of trace elements in fuels and biological materials, (4) development of rapid techniques for the fabrication of planar, lithium-compensated germanium, radiation detectors, and (5) construction and testing of a Mossbauer spectrometer. A summary of these projects follows:

- *Measurement of Vapor Pressures of Metal Chelates.*

The goal of this project is to obtain information on the vapor pressures as a function of temperature for a class of metal chelates being synthesized and studied by the chemistry group at the Aerospace Research Laboratories, Wright-Patterson Air Force Base. The specific class of chelates are those derived from a combination of metals with ligands of acetylacetone, trifluoroacetylacetone, and hexafluoroacetylacetone. The vapor pressure data will provide values of heats of sublimation and vaporization that are needed for elucidation of mechanisms of the separation of the chelates by means of vapor phase chromotography.

Initial measurements of vapor pressure were made by means of the diffusion and isoteniscope methods. At present a quartz spiral Bourdon gauge is being calibrated for the remaining measurements. Present plans are to obtain complete sets of measurements on as many of the transition elements as possible.

- *Fluorescence Lifetime Apparatus.*

Lifetime measurements are essential for the corroboration of some of the mechanisms proposed for energy transfer between selected donors and acceptors as determined by sensitization and quenching of fluorescence studies. Consequently, apparatus for the direct measurement of lifetime is needed at ARL in connection with work on the energy transfer processes which occur in solutions.

Equipment for the direct determination of lifetimes has been essentially completed. The technique employs a nanosecond light pulse from a high pressure, hydrogen-filled lamp, and a fast photomultiplier. The output of the photomultiplier is recorded by the use of a sampling oscilloscope and multichannel analyzer. The lifetime values are obtained by the cross-correlation of phototube response to the excitation light pulse and to the fluorescence radiation.

- *Neutron Activation Analysis.*

The goal of this project is to develop rapid techniques for routine analysis of trace elements in fuels and biological materials. The techniques will be used by the staff of the AFIT Nuclear Engineering Test Facility (NETF) and by personnel of the Flight Dynamics Laboratory and the USAF Hospital, both at Wright-Patterson Air Force Base.

- *Fabrication of Lithium-Compensated Germanium Radiation Detectors.*

There is a need for a ready source of lithium-compensated germanium radiation detector for high resolution gamma spectroscopy. The project was generated at the Flight Dynamics Laboratory, and the radiation detectors will be used by students and scientists at the AFIT NETF. Several radiation detectors using lithium-drift technique have been constructed at AFIT.

- *Mossbauer Spectrometer.*

A Mossbauer spectrometer, based on a design developed by the National Bureau of Standards, was constructed at AFIT. This spectrometer is being used in an advanced laboratory course and for faculty and student research work.

Computational Physics

B. KAPLAN
Associate Professor of Physics

With the advent of high-speed digital computers, it has now become possible to obtain numerical solutions of partial differential equations which satisfy such complex boundary and initial conditions so as not to have solutions in closed form. This class of problems is important in various areas of engineering and applied physics, such as heat transfer and nuclear engineering.

The mathematical technique involved is in the application of finite-difference approximations to convert the original partial differential equation into a set or sets of algebraic equations which can then be solved on the digital computer. However, two fundamental difficulties arise in the process.

- The use of finite difference approximations introduces truncation errors.
- The number of algebraic finite-difference equations, one equation for each mesh point, is usually so large that one is compelled, in general, to use iterative methods of solution for multidimensional problems. These iterative methods can lead to slow convergence, which can become sufficiently acute so as to preclude the use of digital computers for solving partial differential equations.

Using the IBM 7094 computer, the Crandall and Crank-Nicolson methods for solving heat conduction problems were compared with the exact solution found by analytical methods. Accuracy improvement factors and discretization errors were compared for both methods for various grid subdivisions. A range of values of the Fourier modulus and both fixed and convective boundary conditions were used. Two M.S. theses have been written on this subject and one paper has been published.

The problem of slow convergence has been investigated by conducting numerical experiments of the effect of the order of scanning of mesh points on the acceleration of the convergence of iterative solutions by successive over-relaxation. Two M.S. theses have been written on this subject and three papers have been published.

Bioengineering

C. R. REPLOGLE
Assistant Professor of Bioengineering

AFIT research in bioengineering has been extremely diversified, and has been mainly sponsored by the Aerospace Medical Research Laboratories (AMRL). Three areas of research can be identified: human engineering, biodynamics, and bionics.

Research in human engineering has been concerned with the analysis of walking in low-gravity conditions, inertial modeling of man, dynamic response characteristics of weightless man, and visual rendezvous techniques. Much of the effort in biodynamics has been concerned with the modeling and the analysis of biological control systems. Some of the topics include modeling of the intra-aural reflex, servo-analysis of muscle control, analysis of blood-flow control mechanism, dynamic response of organ systems to vibration, analysis of the vestibular system, and whole-body impedance to blast input. The greatest effort in bionics has been directed toward the modeling of brain processes. This includes the simulation of pattern recognition in the visual cortex, neuromine models for muscle control, modeling correlation analysis with neuron-like devices, and pattern recognition with self-organizing machines.

Some of the research in progress is concerned with information-processing techniques and the modeling of biological control systems. Following is a list of the most important projects:

- *A model for renal blood-flow control.*

This project attempts to analyze the method by which the kidney controls the rate of blood flow passing through the organ. It has been found that the organ uses a feed-forward passive mechanism of a type that can be effectively modeled mathematically.

- *A model for correlation analysis using population effects of neuron-like elements.*

This experiment, which uses digital simulation of populations of threshold devices, has shown that it may be possible to use statistical properties of large populations of simple devices to perform complex multivariable correlation analysis at very fast frequencies.

- *Synthesis and simulation of models for information processing in the visual cortex.*

This subject is being explored in depth on a cooperative basis with the Biodynamics and Bionics Division of AMRL.

- *Exploration of methods for studying the otolith system.*

This study is being pursued as M.S. thesis projects.

Since the introduction of bioengineering into the AFIT curricula in 1963, over 50 M.S. theses in bioengineering have been completed. A number of technical reports and papers have been published, and several presentations have been made at professional meetings in both this country and Europe.

Theoretical Plasma Physics

G. K. SOPER
Assistant Professor of Physics

For the past several years research has been conducted in theoretical plasma physics with considerable emphasis on the micro-instabilities or velocity-space instabilities that seem to disrupt the stable confinement of a high-temperature magnetoplasma. Some of this work, which was initiated at the University of Tennessee under the guidance of Dr. Edward C. Harris, dealt with the effects of finite boundaries on plasma stability. In the follow-up work at AFIT, it was found that the model previously used to calculate the boundary effects was in error. Subsequently, modifications were made to the basic model,and the theory was extended and found to be in good agreement with published experimental work. The ion-cyclotron resonance instability theory as first developed by Harris was extended to include finite ion and electron temperature effects. With anisotropic ion and electron temperatures, the dispersion relation, i.e., the equation connecting the wave vector and the frequency of the plasma wave, was solved numerically. The results were shown to be in agreement with some experimental observations.

Currently the growth rates of the unstable ion-cyclotron instabilities for finite temperatures are being investigated. Other work that is being planned will include a theoretical investigation of the effect of beam radial density distribution on charge-charge scattering observations by means of Molière's scattering theory and the determination of the effect of the time-dependent magnetic field perturbation on a finite plasma.

The faculty of the Department of Physics is now collaborating closely with a team of scientists formed at the Aerospace Research Laboratories to study high-temperature plasma physics. The problems to be investigated are the nonlinear effects and thermodynamic descriptions of high-temperature plasmas, with emphasis on microinstabilities.

Electron Paramagnetic Resonance Spectrum of Zinc Selenide Crystals

G. WEPFER, *Captain, USAF*
Assistant Professor of Physics

A study was initiated to investigate the electron paramagnetic resonance (EPR) spectrum of specific zinc selenide crystals. The optical and electrical properties were determined in order to define the defects responsible for the optical and electrical behavior and those responsible for the EPR observations. This led to the formulation of a model for the nature of the imperfection levels observed in these crystals.

Cubic zinc selenide crystals were grown by vapor-phase deposition and were purposely doped with lithium using LiOH in the charge. The EPR spectrum at 77°K consisted of an intense isotropic line at $g = 2.0464 \pm 0.0004$ and a group of angular-dependent lines each of which varied between $g = 2.072 \pm 0.004$ and $g = 6.1 \pm 0.1$ depending on crystalline orientation. The intense line was attributed to the central ($\frac{1}{2} \leftrightarrow -\frac{1}{2}$) transition of Fe^{3+} in a zinc substitutional site. The less-intense angular-dependent lines were attributed to Fe^{3+} in a crystalline field with a strong axial component. The large zero field splitting caused by a selenium vacancy at a nearest neighbor site leaves a spin doublet lowest in energy. Only a transition within this doublet was observed. This led to a single EPR line with $g_{\parallel} \simeq 2$ and $g_{\perp} \simeq 6$ with the parallel direction lying along a line connecting the Fe^{3+} and the selenium vacancy, i.e., a [111] direction. The multiple lines observed are a result of the possible locations for a selenium vacancy.

This work was performed at the Solid State Physics Laboratory of the Aerospace Research Laboratories and was submitted as a dissertation for the Ph.D. degree to the University of Michigan in May 1966. Also, various aspects of the work were reported at the American Physical Society Meetings in August 1965 and August 1966.

systems management

L. L. DUNLAP, *Lt. Colonel, USAF*
Head, Department of Systems Management

The Department of Systems Management, formed in 1963, has initiated and completed a substantial number of research projects in economics, management, operations research, and financial measurement. Many of these efforts have resulted in published papers and textbooks and new programs of study offered by the Department. The studies described in the following paragraphs typify the research endeavors of this Department.

Three major studies were begun in 1966, and in each study, faculty members serve in the dual role of primary researcher and research director. In the latter role, they monitor the contractual support and direct the efforts of temporary research assistants and graduate students whenever their thesis topics coincide with the research goals. Funds for these projects were provided by the Office of Aerospace Research, Washington, D.C. All projects are scheduled to be completed before December 1968. A brief description of each project follows:

1. Under the supervision of this Department, the coordinated efforts of several academic institutions and aerospace companies are directed toward the development of a casebook in weapon systems management. When finished in April 1967, the casebook, complete with teaching notes, will be thoroughly tested in the classroom and subsequently offered for commercial publication.

2. Investigation of the applicability of the manufacturing progress function (learning-curve theory) to current contracting practices will begin in 1967. This project is intended to establish the validity of logarithmic linearity in the learning process in today's weapon development environment where long production runs are rare.

3. The critical-path network techniques will be analyzed for the purpose of developing a method for adjusting time estimates made by contractors. This effort will compare estimates made by contractors for the Department of Defense and NASA with actual schedules. Data will be generated with the cooperation of several aerospace companies and the aid of a temporary research associate.

Since the purpose of the Systems Management Program is to develop middle-management specialists to serve in the weapons acquisition and development functions of the Air Force Systems Command, the initial efforts of the faculty were directed toward the development of a modern curriculum in management. This curriculum is intended to provide officers with a knowledge of the theory and practice of management as it should apply in the defense and aerospace industry environments. This was an intensive effort involving the translation of the needs of the user into courses of study, the comparative analysis of departmental concepts of management education with those of several other leading universities, and an adjustment of the curriculum to accommodate the expected competency of incoming students. The result of this effort is the current program of study leading to a master of science degree in systems management.

In 1964, another curriculum development project was initiated with the cooperation of the Department of Mathematics. The goal of the project was a curriculum leading to a master of science degree in systems analysis. This project required a comprehensive treatment of the methodology and mathematics of analysis of decision in all phases and at all levels of Air Force activity. As a result of this effort, a Systems Analysis Program was approved and the program is scheduled to begin in September 1967 with an annual student input of 25 officers.

An analysis of the operation of the Extension Course Institute (ECI), Gunter Air Force Base, Alabama, was made in 1966 as a faculty-directed student research study. This effort, which was prompted by the general inability of ECI to meet current demands for its services, represented the first organized attempt of the Department to serve in a consulting capacity to Air Force organizations. The results of this study were contained in a detailed report submitted to the ECI Commandant in December 1966.

Future research in the Department of Systems Management will be concentrated on systems analysis and project management, with emphasis on the conceptual foundations for the *decision* and *execution* processes of Air Force management. In particular, systems theory will be used to provide a conceptual basis for the portrayal of a system of interrelated subsystems within an Air Force environment for planning, organizing, and controlling human and materiel resources. Specific research projects on the extension of systems theory to business organizations and the Department of Defense are described below.

1. In the development of a casebook on systems analysis, attention will be focused on the decision process in allocating scarce resources in the acquisition of weapon systems. Research data will be drawn principally from aerospace-industry weapon system development and production examples. Cases designed for use in graduate courses in weapon systems, research and development, and engineering management will provide the graduate student an opportunity to apply the tools of decision-making.

2. The procedures for selecting the source of major weapon systems involve an evaluation of such factors as cost, time, and technology. One criterion used in the evaluation by a selection board is the organization and management capability of the contractor. Information contained in bid proposals submitted to the Air Force has been used principally to determine a contractor's management potential. Research will be focused on determining the ability to predict defense contractor management potential through the use of information contained in the bid proposal.

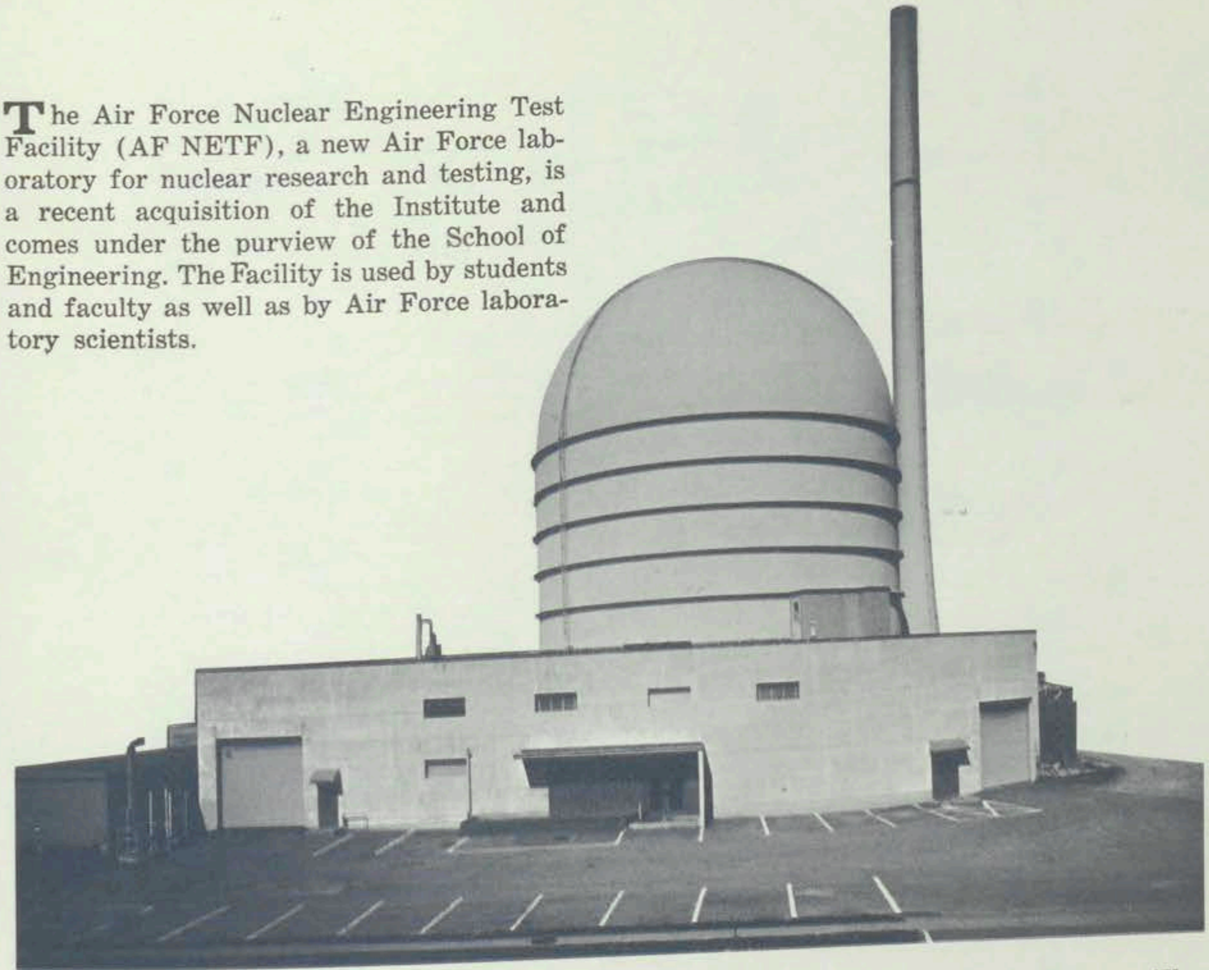
3. Project management is defined as the formation of an interorganizational focal point to manage an ad hoc project. The characteristics and management techniques of a project manager differ significantly from those of the functional manager. The project approach is gaining favor in industry, particularly in cases where the production and marketing strategies for new products do not fit existing commitments of the functional organization. This research will attempt to determine the significance of the project organization in relation to project success by answering the question, "Does the organizational form that is selected for project management have any important effect on the success or failure of a particular project effort?"

4. Members of the faculty will continue to update a weapon systems management casebook developed in a previous research effort. This will require the integration of evolving concepts and practices of weapon systems management used in the Department of Defense.

nuclear engineering test facility

P. S. GWYNN, *Colonel, USAF*
Director, Nuclear Engineering Test Facility

The Air Force Nuclear Engineering Test Facility (AF NETF), a new Air Force laboratory for nuclear research and testing, is a recent acquisition of the Institute and comes under the purview of the School of Engineering. The Facility is used by students and faculty as well as by Air Force laboratory scientists.



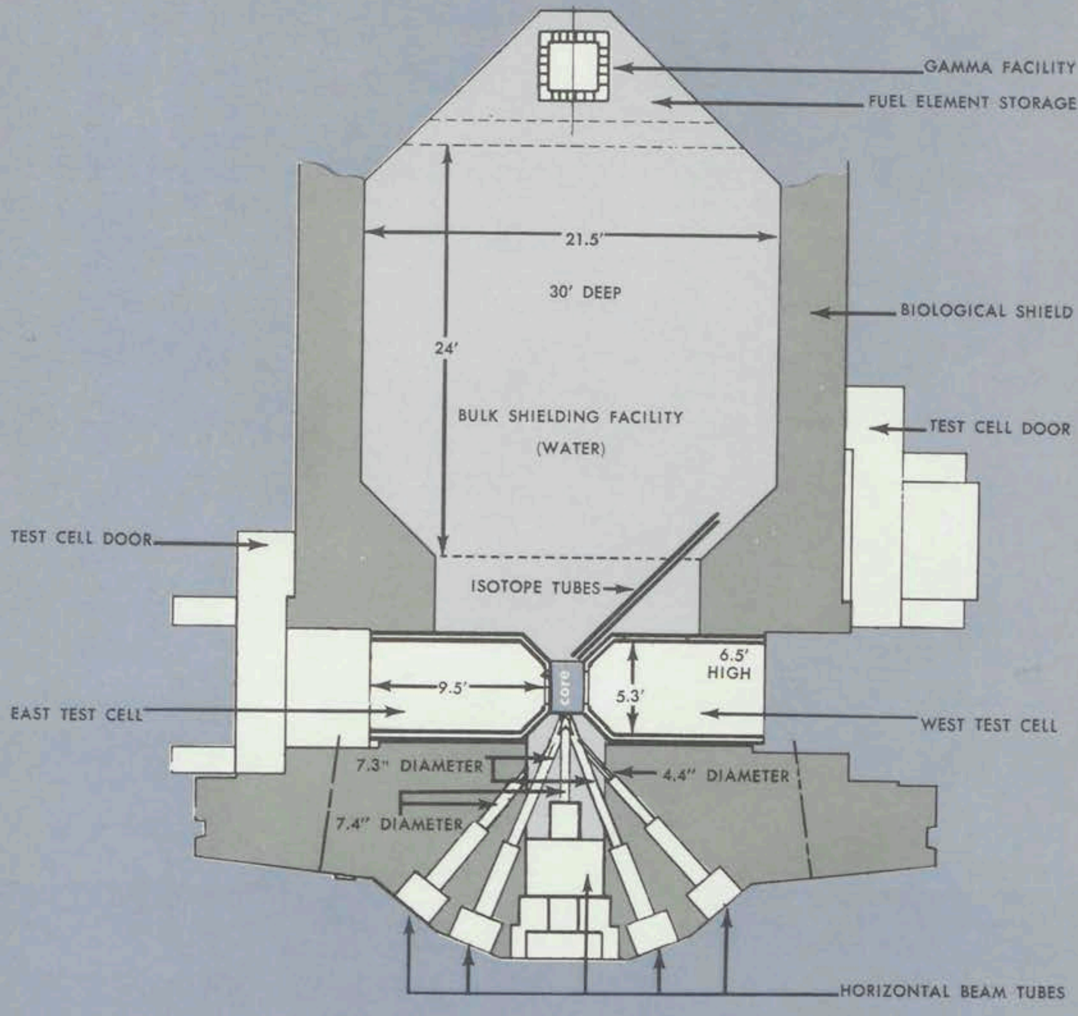
The AF NETF basically consists of a 10 Mw nuclear reactor which is the highest-powered research reactor within the Department of Defense. A large number of experimental facilities are also available for use in a wide variety of environments. Supporting facilities consist of a double-axial/triaxial neutron diffractometer, a Scientific Data System 920 computer for use as a real time data-acquisition and experiment-control system, counting equipment for use in dosimetry and activation analysis, a 700 curie hot cell for remote handling of irradiated material, a 1,500 curie Co^{60} irradiator, a chemistry laboratory, and electronic and machine shop equipment for the support, maintenance, and analysis of experiments.

The experimental techniques available through the use of research reactors represent a vast area of application for the solution of a large number of problems in the scientific and engineering disciplines. The Facility can be used to conduct research in biomedical sciences, nondestructive testing, material testing and development, solid-state and nuclear physics, molecular and crystalline structures, forensics, intelligence appraisal, bionics, electronics, molecular electronics, service engineering, industrial processes, radiochemistry, weapon effects, systems analysis, and aeronautics.

In addition to the experiments carried out for other organizations, the Facility has been used for various studies by AFIT students and faculty. These studies included surface temperature calculations for the reactor, neutron activation analysis (gamma-ray scintillation spectrometry and spectro-analysis), construction and instrumentation of a cryostat for the Facility, flux calculations in the reactor hot cell, and neutron transport calculations.

Air Force Nuclear Engineering Test Facility

Nuclear reactor.



AVAILABLE EXPERIMENTAL FLUXES

Location	Thermal $\varphi < .4$ev n/cm^2 sec	Intermediate $.4\text{ev} < \varphi < .1$Mev n/cm^2 sec	Fast $\phi > .1$Mev n/cm^2 sec	Gamma Dose Rate ergs/gmC hr	Facility Size
In-Core	4.1×10^{13}	1.0×10^{14}	1.7×10^{14}	5×10^{10}	15″ x 21″ x 24″
Test Cells	1.38×10^{12}	3.92×10^{12}	4.49×10^{12}	7.2×10^{9}	5.3′ x 9.5′ x 6.5′
Bulk Shielding Facility	9.07×10^{12}	2.6×10^{12}	1.3×10^{12}	5.4×10^{9}	21.5′ x 24′ x 30′
Isotope Tubes	7.0×10^{12}	2.6×10^{12}	1.3×10^{12}	5.4×10^{9}	4.0″ x 1.5″ ID
Horizontal Beam Tubes (at core face)	8.88×10^{12}	4.12×10^{12}	2.06×10^{12}	1.06×10^{9}	7.4″ ID 7.3″ ID 4.4″ ID
Pneumatic Transfer System	5.03×10^{12}		1.14×10^{12}		4.5″ x 1.5″ ID
Gamma Facility				2.9×10^{8}	12″ x 12″ x 24″

publications

BAILEY, C. D., "Vibration and Buckling of Thermally-Stressed Plates of Trapezoidal Planform," Ph.D. dissertation, Purdue University, January 1962.

BIELKOWICZ, P., "Ground Tracks of Earth-Period (24–Hour) Satellites," *AIAA Journal*, 4, 2190-2195 (1966).

BLAKELOCK, J. H., *Automatic Control of Aircraft and Missiles*, John Wiley and Sons, New York, 1965.

BOHANNON, J. R., "Field Testing the PM–1," *Air Force Civil Engineer*, 3, 2–4 (1962).

______"Nuclear Power Plant Field Tests," *Military Engineer*, 55, 185–186 (1963).

______"The Air Force Nuclear Engineering Test Facility," *Nuclear News*, 8, 22–23, October 1965.

BOOTH, R. S., "Neutron Wave Propagation in a Sub-critical Assembly," M.S. thesis, University of Florida, 1962.

______"Experimentation with Thermal-Neutron Wave Propagation," coauthors, R. B. Perez and R. H. Hartley, *Transactions* of the American Nuclear Society, 6, 287–288 (1963).

______"Propagation of Neutron Waves in Subcritical Assemblies," coauthors, R. B. Perez, R. S. Denning, and R. H. Hartley, *Transactions* of the American Nuclear Society, 7, 49–50 (1964).

______"The Demonstration of Thermalization Effects by the Reflection of Neutron Waves," coauthors, R. S. Denning and R. B. Perez, *Transactions* of the American Nuclear Society, 7, 229–230 (1964).

______"A Theoretical and Experimental Study of Neutron Wave Propagation in Moderating Media," Ph.D. dissertation, University of Florida, 1965.

______"P–1 Space-Energy Dependent Theory of Neutron Wave Propagation," coauthors, H. H. Kunaish and R. B. Perez, *Transactions* of the American Nuclear Society, 8, 272 (1965).

______"Application of Moore's Method to the Analysis of Thermal Neutron-Pulse Propagation Experiments," coauthors, R. H. Hartley and R. B. Perez, *Transactions* of the American Nuclear Society, 8, 291–292 (1965).

______"Excitation of Neutron Waves by Modulated and Pulsed Sources," coauthor, R. B. Perez, *Proceedings* of the Symposium on Pulsed Neutron Research, Karlsruhe, Germany, 10–14 May 1965.

______"The Relative Merits of Impulse and Modulated Sources in Thermal Neutron Wave Experiments," coauthors, R. B. Perez and R. H. Hartley, *Transactions* of the American Nuclear Society, 9, 173 (1966).

______"Propagation of Thermal Neutron Waves in Heterogeneous Media," coauthor, R. B. Perez, *Proceedings* of the Symposium on Neutron Noise, Waves, and Pulse Propagation, University of Florida, February 1966.

______"Theoretical Justification for Neutron-Pulse Propagation Experiments in Fast Nonmoderating Assemblies," coauthor, W. A. Frankhauser, *Proceedings* of the Symposium on Neutron Noise, Waves, and Pulse Propagation, University of Florida, February 1966.

______"A General Polychromatic Telegraphist's Equation for Neutron Thermalization," *Proceedings* of the Symposium on Neutron Noise, Waves, and Pulse Propagation, University of Florida, February 1966.

BOWMAN, G. P., "An Investigation of the Lead Molybdate-Bismuth Molybdate Phase Diagram," *Transactions* of the Metallurgical Society of AIME, coauthors, D. R. Howard, R. K. Saxer, and J. R. Myers, 230, 850–853 (1964).

BOWMAN, R. M., "Shape of Shock Fronts in Shock Tubes," coauthor, H. W. Liepmann, *Physics of Fluids*, 7, 2013–2015 (1964).

______"Investigation of Shock Front Topography in Shock Tubes," Ph.D. dissertation, California Institute of Technology, June 1966.

BREUER, D. W., "Effects of Finite Displacement, Aspect Ratio, and Temperature on the Torsional Stiffness of Cantilever Plates," *Proceedings* of the Fourth U. S. National Congress of Applied Mechanics, ASME, 475–487 (1962).

______"Jet Damping Effects: Theory and Experiment," coauthor, W. R. Southerland, *Journal of Spacecraft and Rockets*, 2, 638–640 (1965).

BRIDGMAN, C. J., "An Analytical Solution of the Neutron Moments Equations," Ph.D. dissertation, North Carolina State University, August 1962.

______"An Analytical Solution of the Neutron Moments Equations," *Proceedings* of the Southwestern Ohio Section of the American Nuclear Society, 1, 87–100 (1962).

______"Simultaneous Size and Radiation Analysis of Radioactive Aerosols Using Electrostatic Precipitation," coauthor, G. Fernandez, *Transactions* of the American Nuclear Society, 7, 336 (1964).

______"Purpose of the ANS Student Conference," *Nuclear News*, 9, 3 (1966).

______"Group Cross-Sections and Constants for Classroom Use," coauthors, E. P. Sims and R. H. Hansen, *Transactions* of the American Nuclear Society, 9, 210 (1966).

______"Kinetic Behavior of a Circulating-Water Reactor Following Large Reactivity Changes," coauthors, J. A. Palmer and D. M. Varelli, *Nuclear Applications*, 2, 81–88 (1966).

BROWN, F. M., "A Node-Elimination Theorem for Boolean Matrices," *IEEE Transactions* on Electronic Computers, EC–12, 133–134 (1963).

______"Code Transformation in Sequential Machines," *IEEE Transactions* on Electronic Computers, EC–14, 822–830 (1965).

______"A Chain-Matrix Development of the Cauer Form," *The Matrix and Tensor Quarterly*, 15, 123–126 (1965).

BURGHART, J. H., "An Adaptive Technique for On-Line Steady-State Optimizing Control," Ph.D. dissertation, Case Institute of Technology, September 1965.

CASEY, K. F., "Transverse Magnetic Wave Propagation in Sinusoidally Stratified Dielectric Media," coauthors, C. Yeh and Z. A. Kaprielian, *IEEE Transactions* on Microwave Theory and Techniques, MTT-13, 297–302 (1965).

———"A Note on Wave Propagation in Periodic Media," *IEEE Transactions* on Microwave Theory and Techniques, **6**, 710–711 (1965).

———"Cerenkov and Transition Radiation in an Inhomogeneous Medium," Ph.D. dissertation, University of Southern California, June 1965.

———"Cerenkov Radiation in Inhomogeneous Periodic Media," coauthors, C. Yeh and Z. A. Kaprielian, *The Physical Review*, **140**, B768–B775 (1965).

———"Reflection and Transmission of Electromagnetic Waves by a Moving Dielectric Slab," coauthor, C. Yeh, *The Physical Review*, **144**, 665–669 (1966).

CHANG, C. S., "An Approximate Method for Solving Optimal Control Problems," coauthor, P. M. DeRusso, *IEEE Transactions* on Automatic Control, AC–**9**, October 1964.

———"An Analytical Method of Obtaining the Root Locus with Positive and Negative Gain," *IEEE Transactions* on Automatic Control, AC–**10**, 92–94 (1965).

———"Discrete Sample Curve Fitting Using Chebyshev Polynomials and the Approximate Determination of Optimal Trajectories Via Dynamic Programming," *IEEE Transactions* on Automatic Control, AC–**11**, 1–8 (1966).

———"The Discrete Orthogonal Property of the Chebyshev Polynomials," *IEEE Transactions* on Automatic Control, AC–11, 144–145 (1966).

CHEATHAM, D. W., "A Microwave Diagnosis of a Cylindrical Plasma with Alkali Metal Injection-Electrical Conductivity," coauthor, J. A. Michollas, *Proceedings* of the 1st Plasma Arc Seminar, September 1963.

———"An Investigation of a Radio Frequency Generated Cylindrical Plasma with Alkali Metal Injection," Ph.D. dissertation, University of Michigan, 1965.

———"An Investigation of a Radio Frequency Generated Cylindrical Plasma with Alkali Metal Injection," *Proceedings* of the 7th Symposium on Engineering Aspects of Magnetohydrodynamics (ASME, IEEE, AIAA), Princeton, March/April 1966.

CLELAND, D. I., "Why Project Management?," *Business Horizons*, Indiana University, **7**, 81–88 (1964).

———"Project Management—An Innovation in Managerial Thought and Theory," *Air University Review*, **16**, 13–22 (1965).

———"The Project Manager—Manager Extraordinary," *Defense Industry Bulletin*, **1**, 1–2, 14, 24 (1965).

———"Contemporary Military Program Management," *California Management Review*, **9**, 1–21 (1966).

———"Changing Patterns in Management Theory," coauthor, D. C. Dellinger, *Defense Industry Bulletin*, **2**, 1–4, 17–20 (1966).

———"Completed Staff Action," *Manage*, **18**, 61–66 (1966).

DAVIS, R. M., "An Experimental Approach to Effective Industrial Communications," Ph.D. dissertation, University of Michigan, 1962.

———"An Experimental Approach to Effective Industrial Communications," *American Business Writing Association Bulletin*, **17**, 9–10 (1962).

———"An Experimental Approach to Effective Technical Writing," *Society of Technical Writers and Publishers Review*, **10**, 24–27 (1963).

———"Effective Mechanical Description: Experiment Two," *Society of Technical Writers and Publishers Review*, **12**, 5–8 (1965).

D'AZZO, J. J., "A Unified Procedure for Deriving the Differential Equations of Electrical and Mechanical Systems," coauthor, G. W. Ogar, *IRE Transactions* on Education, E–5, 18–26 (1962).

———"A Corrected-Conventional Describing Function for Intermediate-Order Nonlinear Control Systems," coauthor, R. R. Rankine, Jr., *NEREM Record*, Session P–1: Automatic Control, **6**, 38–39 (1964).

———"Comparison of the Corrected-Conventional Describing Function with the Elliptic Describing Function," coauthor, R. R. Rankine, Jr., *JACC Record*, Abstracted, June 19, 1964.

———"Control Logic for Attitude Control of a Space Vehicle," coauthor, C. E. Hall, *Proceedings* of the 13th Annual Air Force Science and Engineering Symposium, **3**, September 1966.

———"Feedback Systems Analysis and Synthesis," coauthor, C. H. Houpis, 2nd ed., McGraw-Hill Book Co., New York, 1966.

DOLAN, B. A., "The Mellin Transform for Moment-Generation and for the Probability Density of Products and Quotients of Random Variables," *IEEE Proceedings*, **52**, 1745–1746 (1964).

———"A Generalized Mellin Transform for the Analysis of Learning Machines," Ph.D. dissertation, Stanford University, 1965.

DUNLAP, L. L., "Conveyor Theory: The Individual Station," *AIIE Journal*, **14**, 212-217 (1963).

EDDINGTON, R. B., "Investigation of Shock Phenomena in a Supersonic Two-Phase Tunnel," *AIAA 3rd Aerospace Sciences Meeting*, Paper No. 66–87, January 1966.

ENZER, H., "On a Useful Capital Growth Matrix," *Econometrica*, **34**, 183–192 (1966).

_____"On the Generation of Discount Rates and Implicit Prices Through a Replacement Model," *Management Science*, **13**, 131–143 (1966).

ERICKSON, W. S., "Note on the Equations of Motion of a Rigid Body," *SIAM Review*, 8, 206–210 (1966).

EVANS, D. L., "A Survey of Advances in Solar-Flare Research," *Proceedings* of the Air Force Science and Engineering Symposium, 1, H1–H29, 8–10, October 1963.

_____"Advances in Solar-Flare Research," *Proceedings* of the 10th Air Force Science and Engineering Symposium, October 1963.

FRANKE, M. E., "Thin-Film Heat Transfer Gages," coauthor, J. W. Frye, Jr., *Proceedings* of the 13th Air Force Science and Engineering Symposium, 2, 1966.

_____"The Frequency Response of Pneumatic Lines," coauthor, J. T. Karam, Jr., *Proceedings* of the Joint Automatic Control Conference, 305–311 (1966).

GOODMAN, J. S., "Malayalam Color Categories," *Anthropological Linguistics*, **5**, April 1963.

_____"The Art of Shallow Profundity," *Contact* (AFIT), **17**, June 1963.

GRIMES, C. K., "Wave Propagation in Elastic Solids," Ph.D. dissertation, California Institute of Technology, 1964.

HAND, H. E., "Humanities for Air Force Engineering Students," *College English*, 24, 404–405 (1963).

_____"And War Be Done," Battle-Pieces and Other Civil War Poetry of Herman Melville, *Journal of Human Relations*, 11, 326–340 (1963).

_____"The Indexing of Current Research Information by the Library and Graduate Engineering Students," *College and Research Libraries*, 464–466, November 1963.

_____"An Attempt to Measure Success in Technical Writing," *Journal of Engineering Education*, 55, 69–72 (1964).

_____"A Poem—A Sestet for the Million Monkeys Sitting at Typewriters, Who May Eventually Type *Hamlet*," *Journal of Engineering Education*, **55**, 19 (1964).

_____"Frontiers: Dilemmas of the American Spirit," *Laurel Review*, 13–17 (1965).

_____"The Rise of a Modern American Hero," *Laurel Review*, 14–20 (1966).

_____"The Paper Curtain: The Divided World of Snow and Leavis Revisited," *Journal of Human Relations*, 351–363 (1966).

_____"Transducers and Hemingway's Heroes," *English Journal*, 870–871 (1966).

_____"Introduction to Formal Reports: A Good Start or a Bad Ending?," *Society of Technical Writers and Publishers Review*, **13**, 16–17 (1966).

HANNEN, R. A., "Experimental Determination of a Portion of the Human Vestibular System Response Through Measurement of Eyeball Counterroll," coauthors, M. Kabrisky, C. R. Replogle, V. L. Hartzler, and P. A. Roccaforte, *IEEE Transactions* on Biomedical Engineering, BME–**13**, 65–70 (1966).

_____"A Graduate Bioengineering Program for the Air Force Institute of Technology," coauthors, M. Kabrisky and C. R. Replogle, *IEEE Conference Record*, the Third Rocky Mountain Bioengineering Symposium, F–**62**, 89–93 (1966).

_____"High-Speed Analog Computer Solutions to a Two-Point Boundary-Value Problem," coauthor, V. J. Darcy, *Proceedings* of the 18th Annual National Aerospace Electronics Conference, May 1966.

HITCHCOCK, J. E., "Heat Transfer From Gray Fin-Tube Radiators," coauthor, M. F. Sarabia, *Journal of Heat Transfer*, 88, Series C, 338–340 (1966).

_____"Laminar Forced-Convection in the Entrance Region Between Parallel Flat-Plates," coauthors, W. E. Mercer and W. M. Pearce, *Journal of Heat Transfer*, Paper No. 66–WA/HT–16, 1–6 (1966).

HOLMES, R. B., "Approximation of Bounded Functions by Continuous Functions," coauthor, B. R. Kripke, *Bulletin* of the American Mathematical Society, **71**, 896–897 (1965).

_____"Approximating Best Approximations," *Nieuw Archief voor Wiskunde*, 14, 106–113 (1966).

HOUPIS, C. H., "Parameter Sensitivity by Root Locus," *Control Engineering*, Data File 92, 111–112 (1965).

_____"Root Locus Analysis of a High-Gain Linear System with Variable Coefficients—Application of Horowitz's Method," coauthor, R. H. LaBounty, *IEEE Transactions* on Automatic Control, AC–**11**, 255–263 (1966).

_____*Outline of Pulse Circuits*, coauthor, J. Lubelfeld, Regents Publishing Co., 1966.

_____*Feedback Systems Analysis and Synthesis*, coauthor, J. J. D'Azzo, 2nd ed., McGraw-Hill Book Co., 1966.

JOHNSON, C. L., "Analog Computer Techniques," 2nd ed., McGraw-Hill Book Co., New York, 1963.

JOHNSON, J. H., *Introduction to Electrical Engineering*, International Textbook Co., Scranton, 1965.

JOHNSON, R. W., "Empirical Formulas for Ballistic Re-entry Trajectories," coauthor, R. R. Bate, *ARS Journal*, **32**, 1882–1887 (1962).

_____"Empirical Solution of Re-entry Trajectories," coauthor, R. C. Gibson, *Air, Space and Instruments*, 138–164 (1963).

_____"Results and Techniques for the Guidance and Control of Advanced Ballistic Systems and Aerospace Re-entry Vehicles," coauthors, C. T. Leondes, R. A. Niemann, and J. A. Payne, *Proceedings* of the 10th Symposium on Space and Ballistic Missile Technology, San Diego, August 1965.

———"A Generalized Linear Guidance Law for Aerospace Vehicles," coauthors, C. T. Leondes and J. A. Payne, *Conference Proceedings*, AIAA/JACC Guidance and Control, 361–365, August 1966.

———"Optimum Design and Linear Guidance Law Formulation of Entry Vehicles for Guidance Parameters and Temperature Accumulation Along Optimum Entry Trajectories," Ph.D. dissertation, University of California, January 1966.

JOHNSON, S. W., "Criteria for the Design of Structures for a Permanent Lunar Base," Ph.D. dissertation, University of Illinois, 1964.

KABRISKY, M., *Visual Information Processing in the Human Brain*, University of Illinois Press, 1966.

———"Information Theoretic Limitations Imposed on Models of Human Visual System Function by Cortical Structure," *Proceedings* of the 2nd International Biophysics Congress of the International Organization for Pure and Applied Biophysics, 3.5.2 D15/03, No. 463, September 1966.

———"A Graduate Bioengineering Program for the Air Force Institute of Technology," coauthors, R. A. Hannen and C. R. Replogle, *IEEE Conference Record*, 3rd Annual Rocky Mountain Bioengineering Symposium, F-**62**, 89–93 (1966).

———"Experimental Determination of a Portion of the Human Vestibular System Response Through Measurement of Eyeball Counterroll," coauthors, R. A. Hannen, C. R. Replogle, V. L. Hartzler, and P. A. Roccaforte, *IEEE Transactions* on Biomedical Engineering, BME-**13**, 65–70 (1966).

KAPLAN, B., "Further Notes on Convergence Techniques for Implicit Numerical Solution of the Diffusion Equation for Transient Heat Transfer," coauthor, R. T. Poppe, *Transactions* of the American Nuclear Society, **7**, 5–6 (1964).

———"Acceleration of the Convergence of Successive Over-relaxation by Order of Mesh-Point Scanning in the Solution of the Diffusion Equation for Transient Heat Transfer," coauthor, G. F. Cudahy, *Transactions* of the American Nuclear Society, **9**, 203–204 (1966).

———"A Numerical Comparison of the Crandall and the Crank-Nicolson Implicit Methods for Solving a Diffusion Equation," coauthors, R. C. Campbell and A. H. Moore, *ASME Journal of Heat Transfer*, **88**, Series C, 324–326 (1966).

KING, W. R., "Performance Evaluation in Marketing Systems," *Management Science*, **9**, 563–573 (1963).

———"Marketing Expansion—A Statistical Analysis," *Management Science*, **10**, 659–666 (1964).

———"A Stochastic Personnel-Assignment Model," *Operations Research*, **13**, 67–81 (1965).

———"Toward a Methodology of Market Analysis," *Journal of Marketing Research*, **2**, 236–243 (1965).

———"Early Prediction of New Product Success," *Journal of Advertising Research*, **6**, 8–13 (1966).

KURZENBERGER, J. L., "Motion and Stability of a Rotating Dumbbell-Shaped Satellite Under the Influence of a Gravity Gradient Moment," M.S. dissertation, Air Force Institute of Technology, 1963.

LARSEN, H. C., "Generalized Performance in the Design of COIN Aircraft," *AIAA Conference Proceedings*, General Aviation Aircraft Design and Operations Meeting, Paper No. 64–179, May 1964.

———"Generalized Performance in the Design of COIN Aircraft and Systems," *AIAA Conference Proceedings*, Military Aircraft Systems Meeting, Paper No. 66–779, October 1966.

LUBELFELD, J., "Education in Molecular Electronics," *IRE Transactions* on Education, E-5, 136–139 (1962).

———"A Computer Approach to Laser Design," coauthor, T. G. Purnhagen, *IEEE Transactions* on Electron Devices, ED-**11**, 219–228 (1964).

———"Converting a Pulse Modulator into an Integrated Chip," coauthor, A. J. Wall, *Electronic Design*, 12, 60–62, 64–65 (1964).

———"4-Level Laser Efficiency and Gain Program Operating Instructions," coauthor, T. G. Purnhagen, AFIT-Improved FORTRAN (IBM Catalog No. 01.1.010), 1966.

———*Outline of Pulse Circuits*, coauthor, H. Houpis, Regents Publishing Co., 1966.

MacCULLUM, J. M., JR., "Describing Function Analysis for Nonlinear Sampled Data Control Systems," Ph.D. dissertation, University of Illinois, 1965.

MOORE, A. H., "Extension of Monte Carlo Technique for Obtaining System Reliability Confidence Limits from Component Test Data," *Proceedings* of the 17th National Aerospace Electronics Conference, 459–463, May 1965.

———"Point and Interval Estimators, Based on m Order Statistics, for the Scale Parameter of a Weibull Population with Known Shape Parameter," coauthor, H. L. Harter, *Technometrics*, 7, 405–422 (1965).

———"Maximum-Likelihood Estimation of the Parameters of Gamma and Weibull Populations from Complete and from Censored Samples," coauthor, H. L. Harter, *Technometrics*, 7, 639–643 (1965).

———"One-Order Statistic Estimation of the Scale Parameters of Weibull Populations," coauthor, H. L. Harter, *IEEE Transactions* on Reliability, R-14, 100–106 (1965).

———Review of "Theory of Random Functions and its Application to Control Problems" by V. S. Pugachev, *Industrial Quality Control*, 23, 242 (1966).

———"Local-Maximum Likelihood Estimation of the Parameters of Three Parameter Lognormal Populations from Complete and Censored Samples," coauthor, H. L. Harter, *Journal of the American Statistical Association*, **61**, 842–851 (1966).

———"Iterative Maximum-Likelihood Estimation of the Parameters of Normal Populations from Singly- and Doubly-Censored Samples," coauthor, H. L. Harter, *Biometrika*, **53**, 205–213 (1966).

———"A Numerical Comparison of the Crandall and the Crank-Nicolson Implicit Methods for Solving a Diffusion Equation," coauthors, R. C. Campbell and B. Kaplan, ASME *Journal of Heat Transfer*, **88**, Series C, 324–326 (1966).

———"Point and Interval Estimation, from One-Order Statistic, of the Location Parameter of an Extreme-Value Distribution with Known Scale Parameter and of the Scale Parameter of a Weibull Distribution with Known Shape Parameter," coauthor, H. L. Harter, *IEEE Transactions* on Reliability, R-15, 120–126 (1966).

———"Point and Interval Estimation, from One-Order Statistic, of the Location Parameter of an Extreme-Value Distribution with Known Scale Parameter and of the Scale Parameter of a Weibull Distribution with Known Shape Parameter," coauthor, H. L. Harter, Abstract, *Annals of Mathematical Statistics*, **37**, 542 (1966).

———"Conditional Maximum-Likelihood Estimation from Singly-Censored Samples of the Shape Parameter of the Limited and Pareto Distributions," coauthor, H. L. Harter, Abstract, *Annals of Mathematical Statistics*, **37**, 1420 (1966).

———"One-Order Statistic Conditional Estimators of the Shape Parameters of the Limited and Pareto Distributions and the Scale Parameter of the Type II Asymptotic Distribution of Smallest Values," coauthor, H. L. Harter, Abstract, *Annals of Mathematical Statistics*, **37**, 1420 (1966).

———"Minimum-Likelihood, from Singly-Censored Samples, of the Location Parameter of an Extreme-Value Distribution with Known Scale Parameter," coauthor, H. L. Harter, Abstract, *Annals of Mathematical Statistics*, **37**, 541 (1966).

———"Maximum-Likelihood Estimation from Doubly-Censored Samples of the Parameters of the First Asymptotic Distributions of Extreme-Values," coauthor, H. L. Harter, Abstract, *Annals of Mathematical Statistics*, **3**, 1066–1067 (1966).

MYERS, E. J., "Sectioning of Polyhedrons," *Proceedings* of the First International Congress for Stereology, Vienna, April 1963.

———"Quantitative Metallography for Particles Having Polyhedral Shapes," coauthor, M. J. Sinnott, *Computer Applications in Metallurgical Engineering*, chap. 3, 17–26 (1964).

MYERS, J. R., "Anodic Polarization Behavior of Nickel-Chromium Alloys in Sulfuric Acid Solutions," Ph.D. dissertation, The Ohio State University, 1964.

———"An Investigation of the Lead Molybdate-Bismuth Molybdate Phase Diagram," coauthors, D. R. Howard, G. P. Bowman, and R. K. Saxer, *Transactions* of the Metallurgical Society of AIME, **230**, 850–853 (1964).

———"Corrosion of Beryllium Sheet by Chloride Containing Aqueous Environments," coauthors, R. J. Prochko and R. K. Saxer, *Light Metal Age*, 10–13 (1965).

———"The Effect of Cold Work on the Stress-Corrosion Cracking of Type 302 Austenitic Stainless Steel," coauthors, P. J. Greeley, V. J. Russo, and R. K. Saxer, *Corrosion*, **21**, 327–331 (1965).

———"The Vapor Pressure of Liquid Copper," coauthors, J. M. McCormack and R. K. Saxer, *Journal of Chemistry and Engineering Data*, **10**, 319 (1965).

———"Corrosion of Unstressed Superalloys by Molten Boron Oxide," coauthors, I. P. Graham and R. K. Saxer, *Corrosion*, **21**, 196–206 (1965).

———"Anodic Polarization Behavior of Nickel-Chromium Alloys in Sulfuric Acid Solution," coauthors, F. H. Beck and M. G. Fontana, *Corrosion*, **21**, 277–287 (1965).

———"Influence of Zirconium Additions on the Epsilon Phase of the Titanium-Aluminum System," coauthors, S. V. Spragins and R. K. Saxer, *Nature*, **207**, 183–184 (1965).

———"Threshold Stress and Incubation Period in Stress Corrosion of Types 302 and 316 Wire in Boiling Magnesium Chloride," coauthors, G. H. G. Krafft, J. Z. Amacker, and R. K. Saxer, *Corrosion*, **21**, 188–195 (1965).

———"The Vapor Pressure and Heat of Sublimation of Chromium," coauthors, D. S. Dickson and R. K. Saxer, *Journal of Physical Chemistry*, **69**, November 1965.

———"The Oxidation of René 41 and Thoriated Nickel Filaments," coauthors, R. A. Rosenberg and R. K. Saxer, *SAMPE Journal*, **2**, 10–13 (1966).

———"Corrosion of Beryllium by Salt Water," coauthors, R. J. Prochko and R. K. Saxer, *Materials Protection*, **5**, 39–42 (1966).

———"Thermodynamic Properties of Copper-Platinum Alloys," coauthors, J. M. McCormack and R. K. Saxer, *Transactions* of the Metallurgical Society of AIME, 236, 1635–1637 (1966).

———"The Chemical Activities of Cadmium and Magnesium in Binary Mg-Cd Alloys," coauthors, O. J. Kensok and R. K. Saxer, *Transactions* of the Metallurgical Society of AIME, 236, 938–941 (1966).

———"Effect of Cold Work on Stress Corrosion of Type 309 Austenitic Stainless Steel," coauthors, E. R. Burkart and R. K. Saxer, *Corrosion*, 22, 21–22 (1966).

———"Effect of Grain Size on Stress Corrosion of Type 302 Austenitic Stainless Steel," coauthors, V. L. Barnwell and R. K. Saxer, *Corrosion*, 22, 261–264 (1966).

———"Anodic Polarization Behavior of Low Alloy Steels in Sulfuric Acid Solutions," coauthor, R. K. Saxer, *Corrosion*, 22, 346–348 (1966).

———"Observations on the Anodic Behavior of Nickel and Chromium: Surface Topography and Temperature Effect," coauthors, W. B. Crow, F. H. Beck, and R. K. Saxer, *Corrosion*, 22, 32–38 (1966).

NORRIS, D. O., "A Topology for Mikusinski Operators," *Studia Mathematica*, **24**, 245–255 (1964).

OGAR, G. W., "A Unified Procedure for Deriving the Differential Equations of Electrical and Mechanical Systems," coauthor, J. J. D'Azzo, *IRE Transactions on Education*, E-5, 18–26 (1962).

PERSINGER, C. A., "Subsets of n-Books in E^3," *Pacific Journal of Mathematics*, 17, 1–6 (1966).

———"A Characterization of Tame 2-Spheres in E^3," *Proceedings* of the American Mathematical Society, 17, 213–214 (1966).

POLI, C. R., "A Three-Mass Retrieval Study for the Gemini-Tethered Astronaut," coauthor, E. P. Hanavan, Jr., *Journal of the Astronautical Sciences*, **13**, 61–71 (1966).

———"The Effect of Man's Motion on the Attitude of a Satellite," *Proceedings* of the AIAA/JACC Conference on Guidance and Control, 72–81 (1966).

PRZEMIENIECKI, J. S. "Thermal Stresses," chap. 8, in *Introduction to Structural Problems in Nuclear Reactor Engineering*, Pergamon Press, Oxford, 1962.

———"Note on Cylindrical Bending of a Heated Long Rectangular Plate," *Journal of the Royal Aeronautical Society*, **67**, 65–66 (1963).

———"Matrix Structural Analysis of Substructures," *AIAA Journal*, **1**, 138–147 (1963).

———"Triangular Plate Elements in the Matrix Force Method of Structural Analysis," *AIAA Journal*, **1**, 1895–1898 (1963).

———"Matrix Analysis of Aerospace Structures," *Proceedings* of the 5th International Symposium on Space Technology and Science, Tokyo, 477–500, September 1963.

———"Tetrahedron Elements in the Matrix Force Method of Structural Analysis," *AIAA Journal*, **2**, 1152–1155 (1964).

———Discussion of a Paper on "The Axial Rigidity of a Perforated Strip and the Strain Energy Release in a Centrally-Notched Strip Subjected to Uniaxial Tension," *ASME Transactions*, **86**, Series D, 699 (1964).

———"Alleviation of Thermal Stresses in Bi-Metallic Spar Webs," *Aircraft Engineering*, **37**, 267–272 (1965).

———"Quadratic Matrix Equations for Determining Vibration Modes and Frequencies of Continuous Systems," *Proceedings* of the Conference on Matrix Methods in Structural Mechanics, 26–28 October 1965, Wright-Patterson AFB, Ohio, Report AFFDL TR 66-80, 779–802.

———"Equivalent Mass Matrices for Rectangular Plates in Bending," *AIAA Journal*, **4**, 949–950 (1966).

———"Large Deflections of Diamond-Shaped Frames," coauthors, J. A. Jenkins and T. B. Seitz, *International Journal of Solids and Structures*, **2**, 591–603 (1966).

———"Joining of Complex Substructures by the Matrix Force Method," coauthor, P. H. Denke, *Journal of Aircraft*, **3**, 236–243 (1966).

REGULINSKI, T. R., "Systems Reliability Graduate Curricula," *Proceedings* of the 9th National Symposium on Reliability and Quality Control, 58–61, January 1963.

———*Reliability Engineering Rudiments and Naval Avionics Facility Installation Practices*, U.S. Navy Publication, 1965.

———"Graduate Curriculum in Systems Reliability Engineering," *Annals of the American Institute of Aeronautics and Astronautics*, **5**, 907–910 (1966).

REPLOGLE, C. R., "Experimental Determination of a Portion of the Human Vestibular System Response Through Measurement of Eyeball Counterroll," coauthors, R. A. Hannen, M. Kabrisky, V. L. Hartzler, and P. A. Roccaforte, *IEEE Transactions* on Biomedical Engineering, BME-13, 65–70 (1966).

______"A Graduate Bioengineering Program for the Air Force Institute of Technology," coauthors, R. A. Hannen and M. Kabrisky, *IEEE Conference Record*, **F-62**, 89–93 (1966).

______"A Postgraduate Biomedical Engineering Program," *Proceedings* of the Second International Biophysics Congress, 688 (1966).

ROBISON, W. C., "Use of Parallel Injection for Control of a Bistable Jet," coauthor, P. P. Panzarella, *Journal of Spacecraft and Rockets*, **2**, 1002–1003 (1965).

______"Comments on Chocked Flow: A Generalization of the Concept and Some Experimental Data," coauthor, J. R. Nelson, *AIAA Journal*, **4**, 1309 (1966).

ROMER, E. M., "A Note on a Theorem in Complex Variables," *Mathematics Magazine*, May 1962.

______"An Extension of an Approximation of any Positive Integral Root," *Mathematics Magazine*, May–June 1964.

SAXER, R. K., "The Chemical Activities of Iron and Vanadium in Binary Iron-Vanadium Alloys and Vapor Pressures of Pure Cobalt, Iron, and Vanadium," Ph.D. dissertation, The Ohio State University, 1962.

______"An Investigation of the Lead Molybdate-Bismuth Molybdate Phase Diagram," coauthors, D. R. Howard, G. P. Bowman, and J. R. Myers, *Transactions* of the Metallurgical Society of AIME, **230**, 850–853 (1964).

______"Corrosion of Beryllium Sheet by Chloride Containing Aqueous Environments," coauthors, R. J. Prochko and J. R. Myers, *Light Metal Age*, 10–13, October 1965.

______"The Effect of Cold Work on the Stress-Corrosion Cracking of Type 302 Austenitic Stainless Steel," coauthors, P. J. Greeley, V. J. Russo, and J. R. Myers, *Corrosion*, **21**, 327–331 (1965).

______"The Vapor Pressure of Liquid Copper," coauthors, J. M. McCormack and J. R. Myers, *Journal of Chemistry and Engineering Data*, **10**, 319 (1965).

______"Corrosion of Unstressed Superalloys by Molten Boron Oxide," coauthors, I. P. Graham and J. R. Myers, *Corrosion*, **21**, 196–206 (1965).

______"Influence of Zirconium Additions on the Epsilon Phase of the Titanium Aluminum System," coauthors, S. V. Spragins and J. R. Myers, *Nature*, **207**, 183–184 (1965).

______"Threshold Stress and Incubation Period in Stress Corrosion of Types 302 and 316 Wire in Boiling Magnesium Chloride," coauthors, G. H. G. Krafft, J. Z. Amacker, and J. R. Myers, *Corrosion*, **21**, 188–195 (1965).

______"The Vapor Pressure and Heat of Sublimation of Chromium," coauthors, D. S. Dickson and J. R. Myers, *Journal of Physical Chemistry*, **69**, November 1965.

______"The Oxidation of Rene'41 and Thoriated Nickel Filaments," coauthors, R. A. Rosenberg and J. R. Myers, *SAMPE Journal*, **2**, 10–13 (1966).

______"Corrosion of Beryllium by Salt Water," coauthors, R. J. Prochko and J. R. Myers, *Materials Protection*, **5**, 39–42 (1966).

______"Thermodynamic Properties of Copper-Platinum Alloys," coauthors, J. M. McCormack and J. R. Myers, *Transactions* of the Metallurgical Society of AIME, **236**, 1635–1637 (1966).

______"The Chemical Activities of Cadmium and Magnesium in Binary Mg-Cd Alloys," coauthors, O. J. Kensok and J. R. Myers, *Transactions* of the Metallurgical Society of AIME, **236**, 938–941 (1966).

______"Effect of Cold Work on Stress Corrosion of Type 309 Austenitic Stainless Steel," coauthors, E. R. Burkart and J. R. Myers, *Corrosion*, **22**, 21–22 (1966).

______"Effect of Grain Size on Stress Corrosion of Type 302 Austenitic Stainless Steel," coauthors, V. L. Barnwell and J. R. Myers, *Corrosion*, **22**, 261–264 (1966).

______"Anodic Polarization Behavior of Low Alloy Steels in Sulfuric Acid Solutions," coauthor, J. R. Myers, *Corrosion*, **22**, 346–348 (1966).

______"Observations on the Anodic Behavior of Nickel and Chromium: Surface Topography and Temperature Effect," coauthors, J. R. Myers, W. B. Crow, and F. H. Beck, *Corrosion*, **22**, 32–38 (1966).

SHINE, A. J., "Investigation of Flow in a Truncated Plug Nozzle," coauthor, R. W. Johnson, *ARS Journal*, **32**, 959–961 (1962).

______"Experimental Study of Flow Through Moving Orifices," coauthor, P. F. Meyfarth, *Journal of Basic Engineering*, **87**, Series D, 1082–1083 (1965).

SOPER, G. K., "Studies of the Ion-Cyclotron Resonance Instability," Ph.D. dissertation, University of Tennessee, October 1964.

______"Effect of Finite Ion and Electron Temperatures on the Ion-Cyclotron Resonance Instability," coauthor, E. G. Harris, *The Physics of Fluids*, **8**, 984–990 (1965).

SURRATT, I. W., "Humanities, The Social Studies and Engineering," *Contact* (AFIT), **19**, January 1965.

———"The Statistical Morality of Our Time," *Vanguard*, **53**, 3–5 (1966).

TORVIK, P. J., "Corrugated Addition for Increased Damping in Flexure," coauthor, B. J. Lazan, Abstract, *Journal of the Acoustical Society of America*, **35**, 802 (1963).

———"Dynamic Loads on the Edge of an Elastic Plate," Ph.D. dissertation, University of Minnesota, December 1964.

———"Negative Group Velocities in Semi-infinite Plates," coauthor, R. Plunkett, *Journal of the Acoustical Society of America*, **38**, 924 (1965).

TSONGAS, G. A., "Reverse-Flow Film Cooling of a Small Rocket Engine Chamber," *Journal of Spacecraft and Rockets*, **3**, 444–445 (1966).

VERRELLI, D. M., "Kinetic Behavior of a Circulating-Water Reactor Following Large Reactivity Changes," *Nuclear Applications*, **2**, 81–88 (1966).

WEPFER, G. G., "The Electron Paramagnetic Resonance Spectrum and Related Optical Properties of Trivalent Iron in Cubic and Axial Fields in Zinc Selenide," Ph.D. dissertation, University of Michigan, May 1965.

technical reports

BIELKOWICZ, P., "Lunar Landing and Takeoff," AFIT TR 63-2, May 1963.

———"Comparison of Satellite Ground Track Calculations by RAND and AFIT," AFIT TR 65-14, December 1965.

———"Time Relations and Shape Variation for the Ground Track of the 24-Hour Satellite," AFIT TR 66-12, August 1966.

———"Orbital Time Estimation," AFIT TR 66-13, August 1966.

———"Ground Track of a 24-Hour Satellite," AFIT TR 66-14, August 1966.

———"Non-Coplanar Transfer from Elliptic and Hyperbolic Orbits," AFIT TR 66-17, October 1966.

BOHANNON, J. R., "AFIT-NETF Organizational Functional Structure," AFIT TR 65-11, September 1965.

———"A Review of Technological Applications and Unique Experimental Techniques of Research Reactors and Their By-Products," AFIT TR 66-10, July 1966.

BOWEN, R. M., "Integral and Local Statements of the Balance Equations of Continuum Mechanics for Variable Mass Regions," AFIT TR 64-1, January 1964.

———"A Study of One-Dimensional Magneto Gasdynamics," coauthor, P. W. Tracy, AFIT TR 66-2, February 1966.

BRIDGMAN, C. J., "Auxiliary Space Nuclear Reactor Power," coauthor, P. Orth, AFIT TR 62-3, August 1962.

———"An Analytical Solution of the Boltzmann Equation for Neutron Slowing-Down Length," AFIT TR 62-4, December 1962.

———"Recipes for the Solution of Volterra Integral Equation for Neutron Slowing-Down Length," AFIT TR 62-5, December 1962.

———"Digital Computer Automation of Body Burden Retention Determinations," coauthor, F. S. Dombek, AFIT TR 65-10, August 1965.

———"A Digital Computer Program for Class Scheduling," AFIT TR 66-5, March 1966.

———"Old Barnyard: A Cross-Section Generating Code for Classroom Use—Interim Report," AFIT TR 66-6, May 1966.

BURGHART, J. H. "Evaluation of a Suboptimal Control Technique," Case Institute of Technology, Systems Research Center, Cleveland, SRC 12-C-62-2, May 1962.

———"An Adaptive Technique for On-Line Study-State Optimizing Control," Case Institute of Technology, Systems Research Center, Cleveland, SRC 80-C-65-32, September 1965.

———"An Adaptive Technique for On-Line Steady-State Optimizing Control," AFIT TR 65-13, November 1965.

CHEATHAM, D. W., "An Investigation of a Radio-Frequency-Generated Cylindrical Plasma with Alkali Metal Injector," AFIT TR 65-2, March 1965.

———"Heat Transfer, Normal Stress and Shear Stress for a Free Molecular Gas Impinging on Several Wall Models," coauthor, H. L. Rogler, AFIT TR 66-3, February 1966.

———"Prandtl-Meyer Flow With a Transverse Magnetic Field," coauthor, R. A. Zollner, AFIT TR 66-4, February 1966.

CLELAND, D. I., "The Origin and Development of a Philosophy of Long-Range Planning in American Business." AFIT TR 66-11, July 1966.

CONNER, H. H., Jr., "Photonics Corporation," a case in business administration (10C30), referenced in Intercollegiate Bibliography, Intercollegiate Case Clearing House, Boston, **10** (1966).

———"Photonics Corporation—Teaching Note," a teaching note for a case in business administration (10C30S), referenced in Intercollegiate Bibliography, Intercollegiate Case Clearing House, Boston, **10** (1966).

———"Boston Small Business Investment Corporation," a case in business administration (10F15), referenced in Intercollegiate Bibliography, Intercollegiate Case Clearing House, Boston, **10** (1966).

———"Boston Small Business Investment Corporation—Teaching Note," a teaching note for a case in business administration (10F15S), referenced in Intercollegiate Bibliography, Intercollegiate Case Clearing House, Boston, **10** (1966).

DAVIS, R. M., "Effective Technical Communications: Mechanical Description (Experiment II)," AFIT TR 65-1, September 1965.

———"Effective Technical Communications: Mechanical Description (Experiment III)," AFIT TR 66-15, October 1966.

DOLAN, B. A., "A Generalized Mellin Transform for the Analysis of Learning Machines," AFIT TR 65-9, August 1965.

FASANO, A. N., "North-Phase Research Accommodations at the Air Force Nuclear Engineering Test Facility," coauthor, D. T. Clark, AFIT TR 66-1, January 1966.

GRIFFIN, K., "Analysis of Pin-Jointed Space Frameworks: Nonlinear Effects," AFIT TR 66-16, September 1966.

GRIMES, C. K., "Studies on the Propagation of Elastic Stress Waves in Solid Media," AFIT TR 65-4, April 1965.

———"A Note on Oseen's Improvement of Stoke's Solution to the Problem of Viscous Flow Over a Sphere," AFIT TR 65-7, May 1965.

KAPLAN, B., "Implicit Finite Difference Techniques for Solving Transient Heat Conduction Problems," AFIT TR 64-2, February 1964.

———"Acceleration of the Convergence of Successive Over-Relaxation by Order of Mesh-Point Scanning in the Solution of the Diffusion Equation for Transient Heat Transfer," AFIT TR 66-8, June 1966.

KELLEY, A. E., "Pneumatic Tube Irradiation Facility," AFIT TR 65-12, September 1965.

LARSEN, H. C., "Counterinsurgency Study, Vol. I, Chapter 3: Aircraft," Aeronautical Systems Division, ASD-TDR-63-292-Vol. I, 1963.

_____"Counterinsurgency Study, Vol. III: Aircraft," Aeronautical Systems Division, ASD-TDR-63-292-Vol. III, 1963.

_____"COIN Aircraft, Part I—Summary Report (Interim)," Systems Engineering Group, 64-SES-5843, 1964.

LEHMANN, W. L., "Material Strength Properties Under Dynamic Loading," coauthor, J. Webster, AFIT TR 65-8, July 1965.

MacCULLUM, J. M., Jr., "Describing Function Analysis for Nonlinear Sampled-Data Control Systems," AFIT TR 65-5, May 1965.

MOORE, A. H., "Implicit Finite Difference Techniques for Solving Transient Heat Conduction Problems," AFIT TR 64-2, February 1964.

_____"Point and Interval Estimates of the Scale Parameter of Weibull Populations Using Point and Interval Estimates for Exponential Populations," AFIT TR 64-3, March 1964.

MYERS, E. J., "Quantitative Metallography for Particles Having Polyhedral Shapes," coauthor, M. J. Sinnott, American Society for Metals, Tech. Rpt. 16-4, October 1963.

POLI, C. R., "Counterinsurgency Study, Vol. VII: Patrols and Encounters," Aeronautical Systems Division, ASD TR 63-292, 1963.

_____"Study of Low-Attitude Decoys for the B-52," Systems Engineering Group, SEG TR 64-12, March 1964.

_____"A Three-Mass Retrieval Study for the Gemini-Tethered Astronaut," Systems Engineering Group, SEG TR 65-29, July 1965.

_____"A Study of Retrieval Techniques for Tethered Astronauts," Systems Engineering Group, SEG TR 65-30, July 1965.

_____"A Study of the Effect of Man's Motion on the Attitude and Orbital Motion of a Satellite," Systems Engineering Group, SEG TR 65-41, December 1965.

PRZEMIENIECKI, J. S., "Alleviation of Thermal Stresses in a Skin-Web Combination by Means of a Bi-Metallic Construction," Aerospace Research Laboratories, ARL 64-108, June 1964.

_____"Joining of Complex Substructures by the Matrix Force Method," Douglas Aircraft Company, Long Beach, California, Tech. Rpt., LB-32038, November 1964.

_____"Digital Computer Program for the Analysis of Aerospace Structures by the Matrix Displacement Method," Air Force Flight Dynamics Laboratory, FDL TR 64-18, April 1964.

REGULINSKI, T. L., "Reliability Prediction Study of Telemetry Multiplexer and Transmitter," AFIT TR 66-18, October 1966.

RICHARD, C. W., Jr., "Nyquist and Bode Plots Using an Analog Computer," AFIT TR 63-4, November 1963.

_____"A Digital Computer Program for Class Scheduling," AFIT TR 66-5, March 1966.

ROMER, E. M., "Orbital Transfer Problems," AFIT TR 62-1, January 1962.

_____"Recursion Formulae to Obtain Integral Roots of Real Numbers," AFIT TR 63-1, March 1963.

_____"Higher Order Recursion Formulae for Integral Roots of Real Numbers," AFIT TR 63-3, September 1963.

TORVIK, P. J., "Damping of Materials Under Biaxial Stress," Aeronautical Systems Division, ASD TDR 62-1030, May 1963.

_____"A Corrugated Addition for Increased Damping on Flexure," Air Force Materials Laboratory, AFML TR 64-373, January 1965.

VALLISH, E. J., "Bulk Shield Facility Irradiation Accommodations at the AF-NETF," AFIT TR 66-9, June 1966.

VERRELLI, D. M., "Air Force Nuclear Engineering Test Facility (NETF) Operations Plan," AFIT TR 65-3, March 1965.

_____"An NETF Technical Specification," AFIT TR 65-6, May 1965.

WEPFER, G. G., "Effects of Optical and Microwave Radiation on Solid State Imperfections," Aerospace Research Laboratories, ARL 65-1, January 1965.

WHITTENBERGER, W. W., "A Message for Determining the Radioactivity of an Experiment After It Has Been Irradiated in the AFIT-NETF," AFIT TR 66-7, June 1966.

This publication has been reviewed and approved by competent personnel of the preparing command in accordance with current directives on doctrine, policy, essentiality, propriety, and quality.

WRIGHT-PATTERSON AIR FORCE BASE, OHIO